FRICTION AND WEAR BEHAVIOUR OF CENOSPHERE DISPERSED ALUMINIUM MATRIX COMPOSITE FABRICATED BY

POWDER METALLURGY ROUTE

A thesis submitted to

National Institute of Technology, Rourkela

In partial fulfilment of the requirement for the degree of

MASTER OF TECHNOLOGY

In

Mechanical Engineering
(Specialization: *Machine Design & Analysis*)

By

RAMA PRASANNA PRADHAN

Department of Mechanical Engineering

National Institute of Technology

Rourkela – 769008 (India)

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RAMA PRASANNA PRADHAN
(213ME1387)

Under the Supervision of

Prof. Samir Kumar Acharya
Department of Mechanical Engineering, NIT, Rourkela

Department of Mechanical Engineering

National Institute of Technology

Rourkela – 769008 (India)

May, 2015

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

CERTIFICATE

This is to certify that the work in this thesis entitled, "**FRICTION AND WEAR BEHAVIOUR OF CENOSPHERE DISPERSED ALUMINIUM MATRIX COMPOSITE FABRICATED BYPOWDER METALLURGY ROUTE**" submitted by **RAMA PRASANNA PRADHAN (213ME1387)** for the award of the Master of Technology in Mechanical Engineering with specialization in Machine Design and Analysis, is a record of bonafide research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma.

The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of Master of Technology in accordance with regulations of the Institute.

Place: Rourkela
Date: 26th May, 2015

Prof.S. K. Acharya
Dept. of Mechanical Engineering
National Institute of Technology,
Rourkela-769008

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Rourkela

Date: 26th May 2015 **(Rama Prasanna Pradhan)**

ABSTRACT

In the Present work cenosphere dispersed aluminium matrix composites were fabricated by powder metallurgy route. The friction and wear behaviour of these composites were studied by using a pin on disc machine. Various weight percentages of cenospheres (10, 20, & 30 wt. %) were reinforced with pure aluminium. The results showed that density decreases with addition of cenospheres but hardness increases with addition of cenosphere particles. The dry sliding wear mechanism was also established and presented in detail. The sliding wear test shows a significant improvement in wear resistance of pure aluminium with addition of cenosphere particles. SEM studies were also carried out to know the wear surface morphology of the products.

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NOMENCLATURE

F	Load (N)
VHN	Vickers Hardness
MMCs	Metal Matrix Composites
c/s	Cenosphere
ρ	Density of the target material (gm / cm^3)
ρ_f	Density of filler (gm / cm^3)
ρ_m	Density of Matrix (gm / cm^3)
ρ_{th}	Theoretical Density (gm / cm^3)
ρ_{act}	Actual Density (gm / cm^3)
Δm	Mass loss (gm)
S_d	Sliding Distance (m)
W	Abrasive wear rate (m^3/m)
W_s	Specific wear rate (m^3/Nm)
W_v	Volumetric wear rate (m^3/sec)

Dedicated

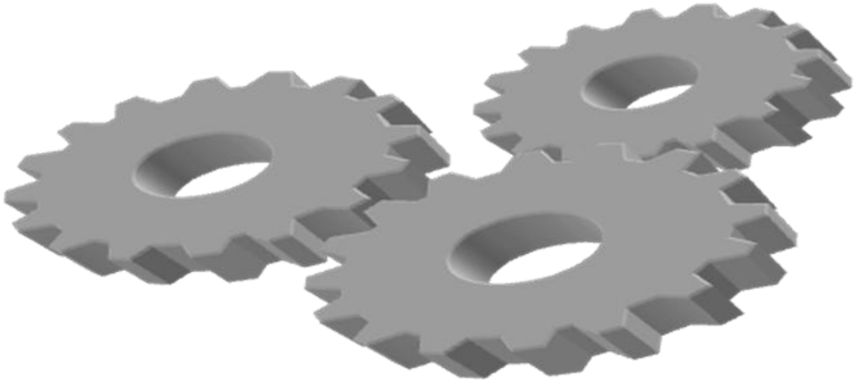
to

My Beloved Son,

&

My Family

Whose love, blessings and sacrifice brought me here up to……



INTRODUCTION

1.1 RESEARCH BACKGROUND

Referring to the past history, we can understand the fact very well, technically.

Looking towards the past, history can well be understood by the technological constituents (materials) and technical expertise which reflects the individual potential as well as perceptive. Time and again vision starts with thousands of years before, where many metals like Iron, Bronze, steel, Aluminium and various alloys came into picture, which led to the improvements in the designing, in the field of metallurgy, production etc. that were carried out. Engineering made all these process achievable to go ahead forward and found additional superior resources that can be practicable.

Conventionally, some of the properties of the materials like density, frictional resistance, strength, hardness in addition to tribological characteristics, which are some of the most important parameters to be accounted, in the field of design of materials, which may be problematic considering conventional materials. So to technically design a subject, these properties should be taken into account. To meet these aspects of practical demand, and to fulfil technically the ever increasing demand of modern day technical aspects, composites are taken into account as the competent material of current trends and demand.

Evolution in the developments of composites started from early 1940s to recent polyamides/metal composites, those are used in advanced space ships / station – is amazing. The identification of the prospective burden savings that are achievable implementing more highly developed composites, possibly meaning abridged expenditure as well as increased effectiveness, are accountable for the development in the technical aspects of reinforcements, matrix with production of composites. Initially, starting phase worked with and went ahead with the fabricating methods, tribological aspects, fracture mechanics and systematic study of different technical properties of the prepared composites, were the focal regions in 1960s. From this period the demand of newer, stronger, having better stiffness and wear characteristic yet being cost – effective and possessing reduced weight value, materials in fields such as automobiles, aeronautical, transport sectors is growing rapidly. Recently the demand for composite materials is growing mainly responding to unmatched demand from technical fields due to speedily growing activities in aeronautical and automobile sectors. These composites possess reduced specific gravity from monolithic material, that enhances their properties specially in modulus and strength as compared to other materials mainly metals[1].

Studying intensively the basic nature of materials and improved consideration of their structural behaviour, developing newer and better composites having highly improved physical, chemical, tribological properties etc. has become achievable. These newly developed materials includes highly developed performance composites such as Metal Matrix Composites(MMCs)[2], Polymer Matrix Composites (PMCs)[3,4], Ceramic Matrix Composites (CMCs)[5,6], but out of these metal matrix composites are more advanced and developed composites, utilized in most engineering sectors, which consists of two or more constituents, out of which major constituent is compulsory a metal, used as a matrix, and some materials used as reinforcements, resulting establishing the desired properties for application. Continuous advancements in the technical field has progressed the use of composite materials viz. MMCs, PMCs, CMCs, in the vast diversified applications. Here a fact can be taken into account, which is a very important factor, in the field of technology. Today among 1500 engineering materials are available worldwide, over 300 types of materials are composites [7], where the fraction is growing each and every hour and every day.

1.2 Composites.

1.2.1 Definition of Composites.

Composites are the material systems, which comprises of two or more than two constituents (mixed and bonded) on a macroscopic scale [8]. Composites comprises of more than one irregular phases surrounded in an uninterrupted phase. The irregular phase is generally stronger and harder in comparison to the uninterrupted phase and is called the 'reinforcement' or 'reinforcing constituent', while the uninterrupted phase is synonymed as the 'matrix'. Commonly, a composite matter comprises of reinforcement (fibers, particles, flakes, and/or fillers) rooted in a matrix or medium (metals, as in this case). The main objective of the matrix is to hold the reinforcements to design and fabricate the required shape, where as the reinforcement increases drastically the general mechanical properties of the matrix. When designed appropriately, the novel combination of material presents improved strength, which the individual material would not have showed.

Jartiz [9] researched that the composite materials are the material systems which provide the characteristics, which are not accessible from any distinct material. They are consistent structures formed by combining two or more well-matched constituents, which are dissimilar in composition and description.

1.2.2 Why Composites?

Considering the past, over the last fifty years, the applications of future materials like ceramics, plastics are creating a high demand in the technical sector, in comparison to the monolithic materials. Among these, some developed materials like composites are emerging steadily, because of their superior properties, both in engineering as well as non - engineering applications.

1.2.3 Classification

One can classify the composite in several dissimilar ways.[10, 11] But a distinctive categorization is presented in the **Fig. 1.1**

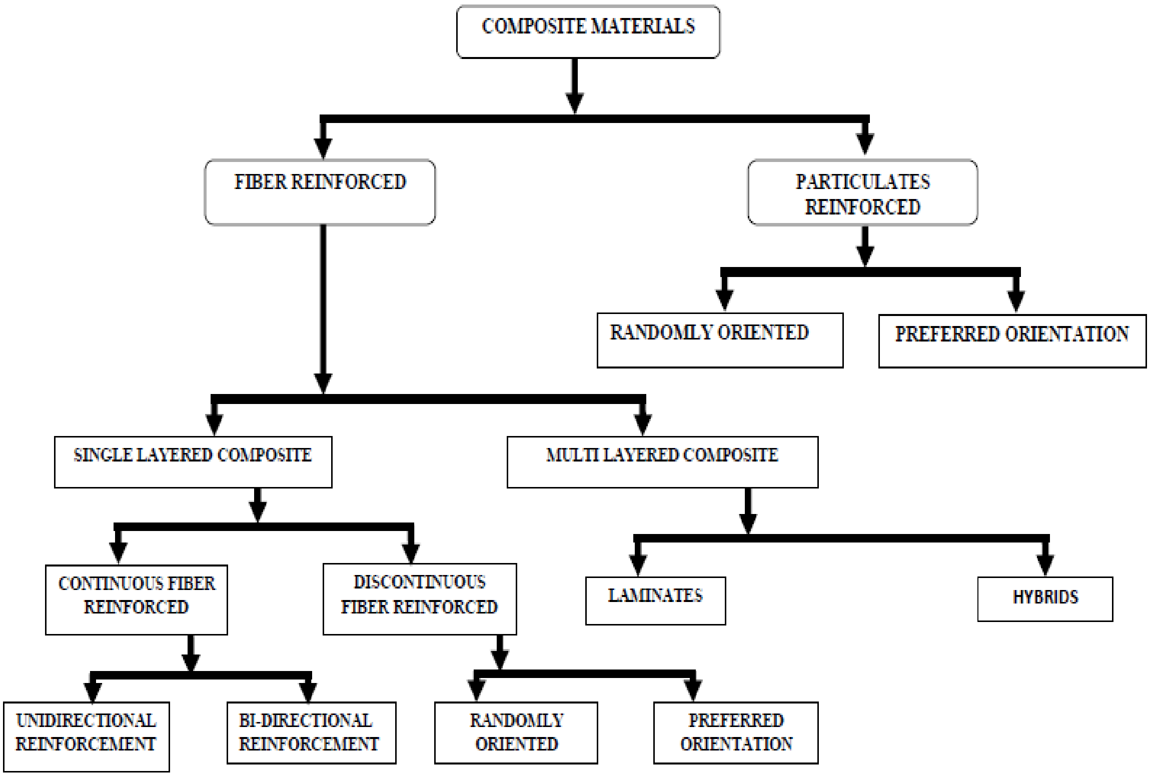


Fig1.1

1.2.4 Components of a composite

As discussed earlier, a composite material consist of minimum of two constituents, working together, to generate material properties those are dissimilar to the properties of the individual constituents. Practically, composites mainly consist of a bulkiness material, which is termed as 'Matrix', and reinforcements /fillers generally possessing some particular parameters, which are supplementary added basically to enhance the strength, stiffness as well as the required properties of the matrix, and, finally improve the desired properties of the prepared composites.

1.2.5 Role of Matrix

Many materials, in a particulate form, shows very superior mechanical as well as metallurgical properties, but to accomplish these properties, the fillers has to be bonded by appropriate matrix. The matrix separately holds the fillers from together. In order to avoid abrasion and establishment of new surface deficiencies, but also prove itself as a connection to hold the fillers in place. A high-quality matrix should always possess the capability to distort effortlessly under practical load, relocate the load among the reinforcements and consistently distributed stress concentration.

1.2.6 Need for Reinforcements in Composites

The reinforcement material, or fillers as in this case study, is surrounded into a matrix. The reinforcement always does not provide a solely structural assignment (i.e. reinforcing the compound), as the name suggests, but also is used to alter the mechanical properties such as wear resistance, frictional coefficient, thermal conductivity etc. Either continuous or discontinuous reinforcements can exist. Isotropic discontinuous metal matrix composites can be worked with touchstone metalworking routes, such as extrusion, forging, or rolling. A brief idea about reinforcements is shown in Fig. 1.2

1.3 Aluminium Metal Matrix Composites (AMMCs)

Most metals have been experimentally used, as well as industrially implemented, as matrix for metal matrix composites, like aluminium, titanium, magnesium etc., while the fillers that can be used, can be long fibers, short fibers, whiskers, particles with equal axis properties and interrelated networks [12].Metal matrix composites (MMCs) which are based on pure aluminium (AMMCs), can be applied for engineering / non-engineering implementations, serving enhanced physical, mechanical and tribological properties in comparison to pure aluminium. Particularly, MMCs those are reinforced with ceramic fillers may offer enhanced strength, stiffness, hardness property [13].Prediction of composite behaviour continues to

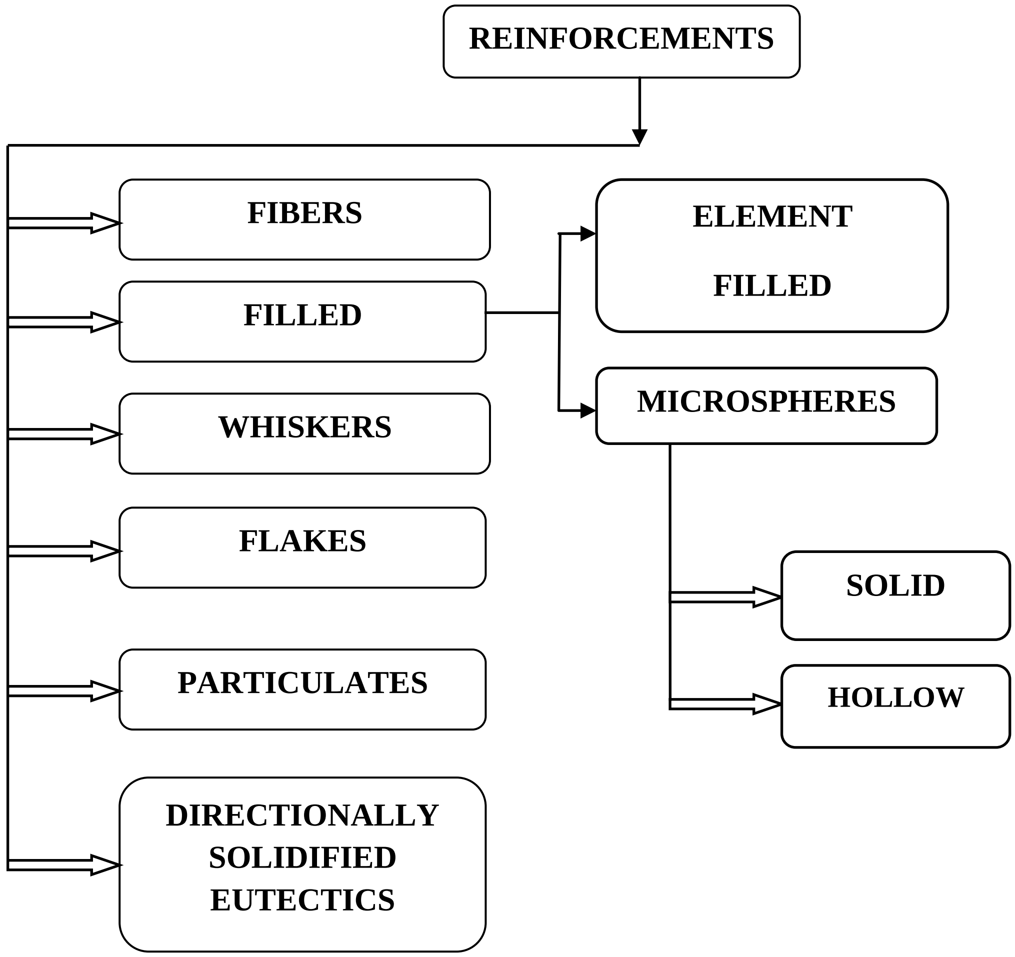


Fig1.2 Reinforcements

develop with improved scientific knowledge and modelling capacity, forwarding enhanced successful as well as dependable use of these compound materials. [14].AMMC's have been experienced and proved beneficial in miscellaneously varied engineering sectors including functional and structural applications, for the reason that of, variation in mechanical properties of the composites depending upon the proportion of reinforcement and chemical composition of Aluminium matrix can be achieved.

1.3.1 Application of Aluminium Matrix Composites

Applications, along with the usage of Aluminium Matrix Composites (AMMCs) include a wide variety of products and processes. They can be broadly put into the following categories:

1.3.1.1 High performance areas.

This forms the high tech end of the spectrum and comprises mainly of aerospace sectors, as for a recent example, Airbus 380, and other aeronautical fields, with applications in aircraft launch, chemical satellites, missiles etc. The volume of consumption is low, relating to the given examples, but the technological requirements are of higher order.

1.3.1.2 High Volume / Commercial areas.

This consists of very huge range of products, both in engineering as well as consumer sector items which are generally produced commercially. A mainly application focuses upon agriculture, automotive/transportation, pollution control and general engineering sectors.

1.3.1.3 Speciality Areas.

This area focuses on special applications where technology level as well as volume level dramatically varies as per the requirements but, special consideration overcomes the factor of product development. These include bio-medical applications and other specialized areas.

1.4 Cenospheres

Among a range of fillers used, fly ash is among one of the majority of economical and having the property of low compactness, reinforcement accessible in huge amounts as solid waste by-product in the process of ignition of coal in thermal power plants. Particles of fly-ash can generally be classified into two types: precipitator fly ash; cenosphere fly ash.

In this study we are focussing on cenosphere fly ash. The term "cenosphere" is resoluted from the Greek words:

- "*Kenos"* (empty); and
- "*Sphaira"* (sphere).

Cenospheres are frivolous, inactive, and vacant spheres, fundamentally comprising of silica and alumina, which are packed with air or inert gases, and are generated resulting from the combustion of pulverised coal at the thermal power plants. A typical micro-photograph of cenosphere particles are shown in the **fig1.3.**

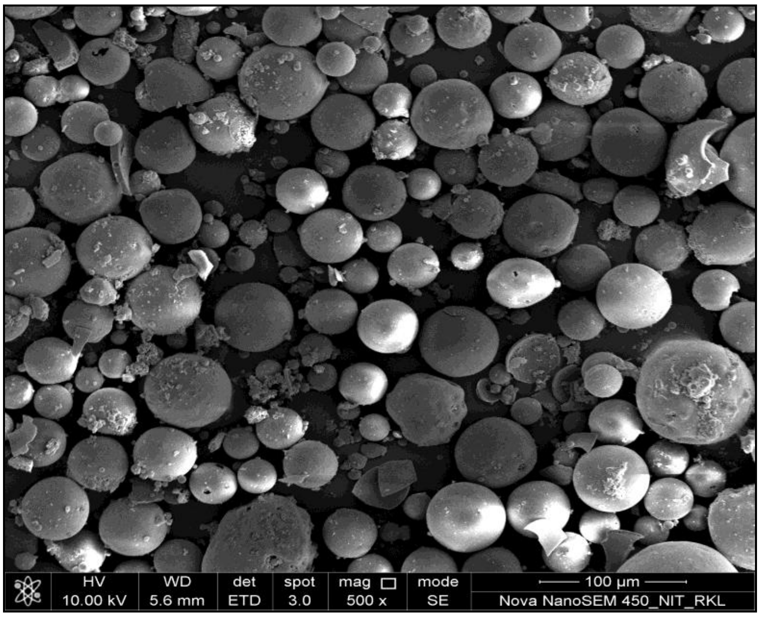


Fig. 1.3 Micrograph of Cenosphere particles

Cenospheres can be utilized in plastics, light weight panels, agricultural products, aeronautical and space fields, and almost in all sectors, where conventional fillers can be utilized. Due to their flexibility in the field of application, they can be and are being used in many high technology and traditional industries.

1.5 Wear

At the instant, when two material surfaces are in contact or in sliding motion among each other, with relative motion among them, there is some measurable elimination of matter. This process of elimination of material is known as wear. This process results in damage to the contacting surfaces. Practically each and every material gets worn out due to this phenomenon. This phenomenon has been observed from a much stretched period, by each and every body [15]. We can define wear as: -*the damage done to a contacting surface, usually concerning subsequent depreciation of material, because of the relative motion among the contacting surfaces [ASTM 1999]*.In most cases wear occurs through surface connections at asperities as shown in the **fig**.**1.4.**

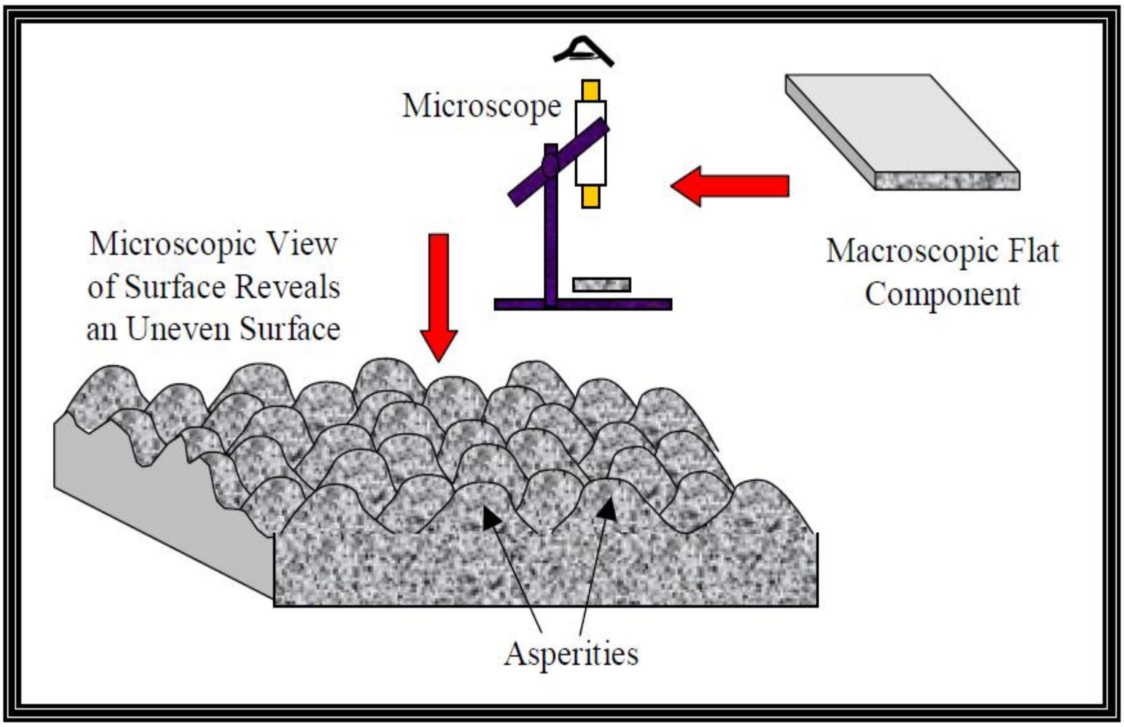


Fig. 1.4 Asperities present on the surface

Now-a-days, investigational tests of wear intensities of materials belong to benchmark measurements of mechanical properties of solids. Yet, anyhow, it is difficult to predict and to control wear of rubbing elements.

1.5.1 Descriptive key terms

Wear phenomenon can be well described by using various terms, and they individually are not at all times well differentiated. Resulting that occasionally it makes the perceptive of wear behaviours perplexing and rather complicated. Hence additional research work should be held in order to accomplish superior clarity in the approach for the investigation of wear mechanisms. Here, in this segment, vivid explanation of wear and their correlations are detailed and shown in **Fig. 1.5**

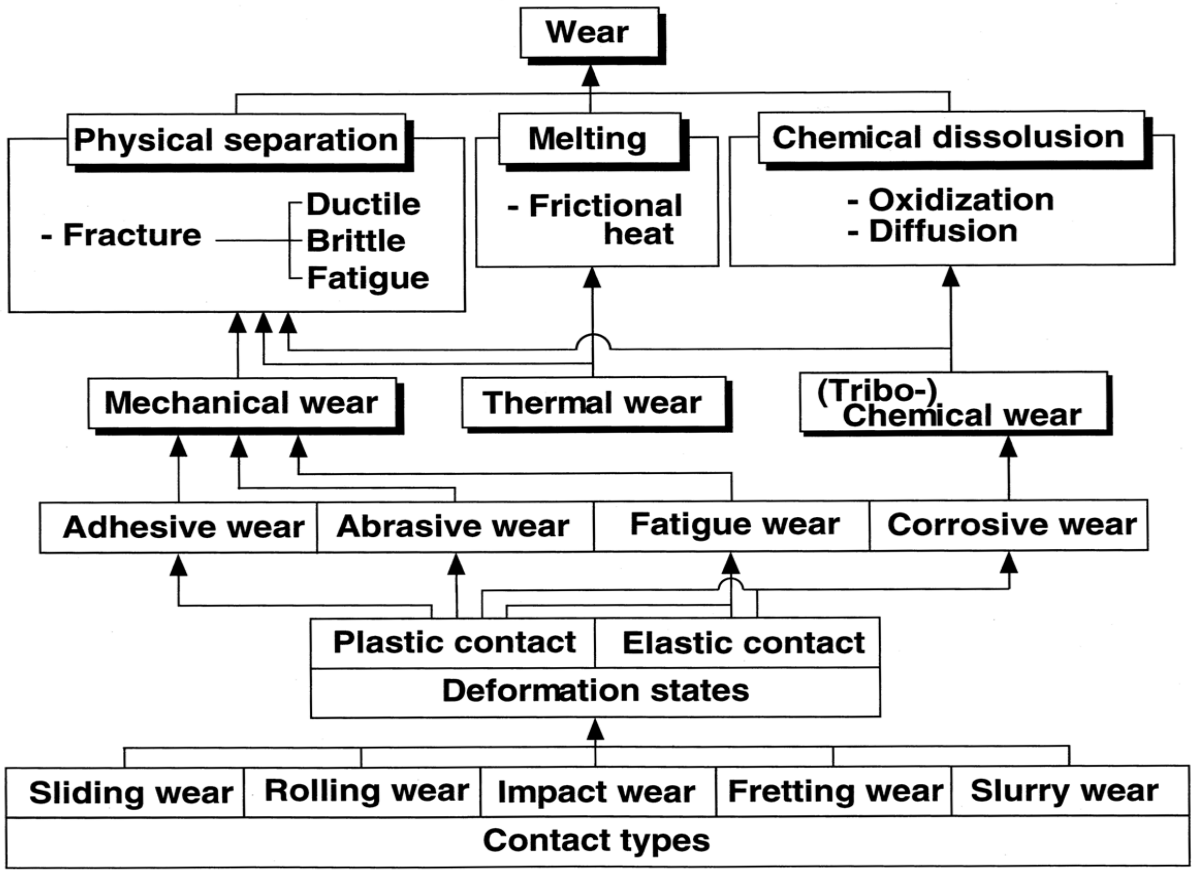


Fig. 1.5 Wear Description

1.5.2 Abrasive wear:

Here in this work, the investigation is basically with abrasive wear. The wear that occurs when a hard surface slides against and cuts groove from a softer surface is defined as Abrasive wear. It can be reason for most failures in practice. Hard particles on asperities that results in a cut on one of the rubbing surfaces results in abrasive wear. The hard particles may be originated from one of the two rubbing surfaces. The phenomenon of abrasive wear can be understood by the fig.1.6.

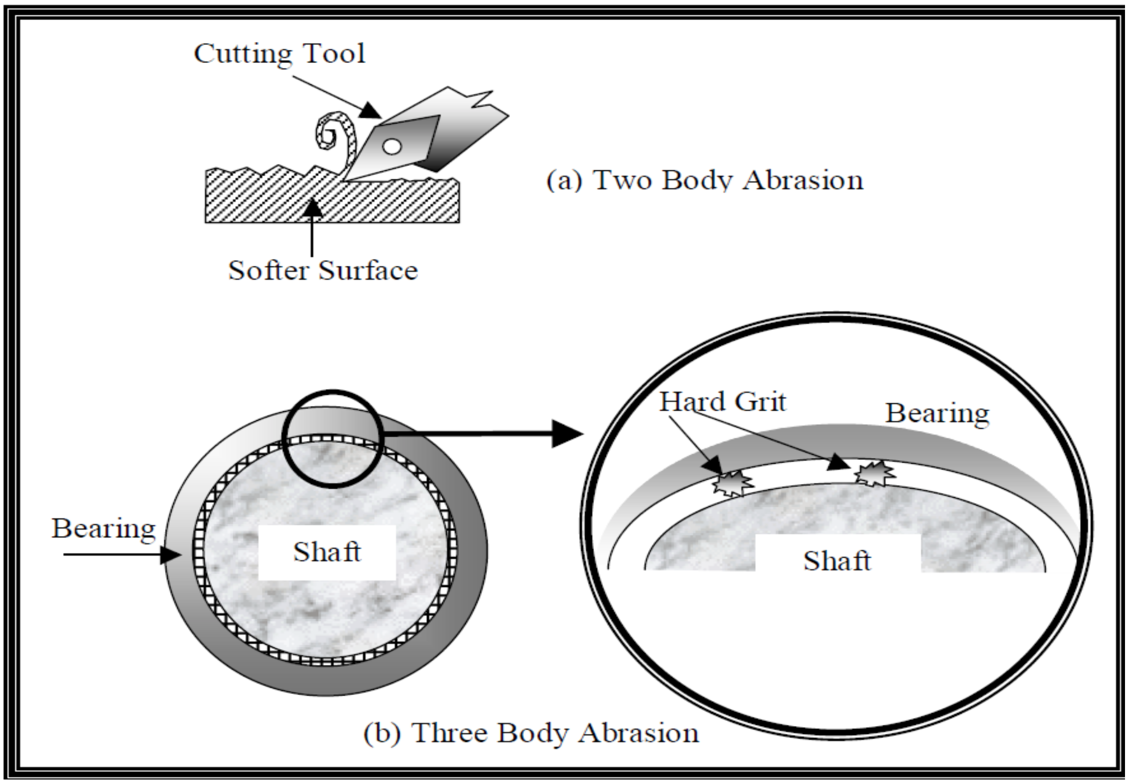


Fig. 1.6 Phenomenon of Abrasive wear

Abrasive wear occur under two conditions

(i) Two body abrasion:

In this circumstance, out of the two contacting surfaces in rubbing action, one is harder than the other, resulting in wear, as shown in the figure 1.6.

(ii) In three body abrasion:

In this circumstance, hard particles are there between two rubbing surfacescausing the surfaces to experience abrasive wear. As per the current tribological research, abrasive wear phenomenon is responsible for the major material thrashing in engineering applications as shown in figure 1.6.

1.6 Problem Findings and Thesis outline:

The purpose of present work is to examine and investigate the possibility of Cenospheres as filler material in Aluminium powder matrix, to fabricate the composite via Powder Metallurgy

(P/M) route, and to explore its effects on mechanical and tribological properties of resulting composites.

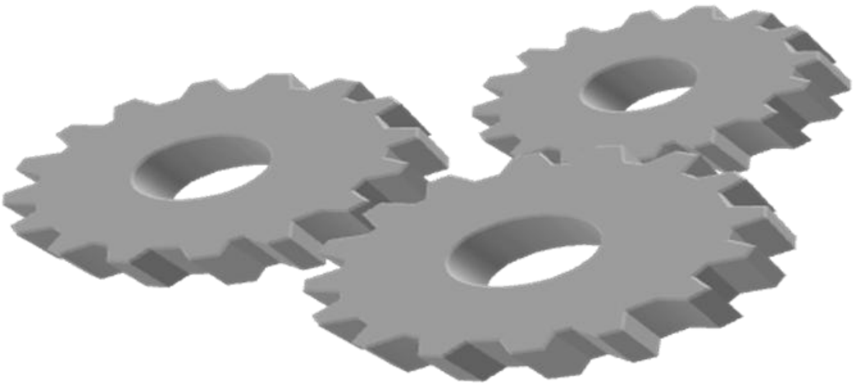
In this work effort has been applied by using different proportion of cenosphere particle to determine a potentially possible utilization of cenosphere that can be productively applicable as particulate filler in Aluminium matrix for evolving high strength and wear resistant composites. The following part of thesis is compiled as follows:

Chapter 2: Earlier effort relevant to the existing analysis accessible in literature is reported in given chapter.

Chapter 3: Illustration of the materials and process or methods employed is described in this chapter.

Chapter 4: In this chapter testing results for the mechanical characteristics and abrading performance of the composites investigated.

Chapter 5: Deduction from the research effort and proposal for perspective or future work are submitted in the given chapter.



LITERATURE SURVEY

2.1 INTRODUCTION

From the recent past, many research and development work in tribology is being focussing on to find the sliding and rolling pairs, being able to meet the harsh conditions of tribological systems, operating in heavy duty circumstances: under significant load, at high speed, varying temperature and contaminated surroundings etc.

Suitable chosen new materials, e.g. proper reinforced composites, can fulfil these severe conditions. Metal matrix composites, filled with non-metallic fillers in the form of fibers, particles or whiskers and solid lubricants may have superior mechanical and tribological properties. These materials have to be proficient to support adequately major load without unnecessary alteration, deformation or rupture during performance and to keep up controlled friction and wear over elongated periods.

Some of the past researches and findings in these fields are reported in this chapter. This chapter deals with literatures related to Metal Matrix Composites (MMCs), theories of wear and wear behaviour of composites, implementation of Aluminium as matrix in MMCs, Cenospheres as reinforcements in MMCs. Gaps in the literature review have been identified.

Prasad Naresh& Acharya S.K [16] focussed that, the literature study is carried out as a division of the thesis work, to have a detailed general idea of the fabrication method of the composites, properties and wear performance of metal matrix composites (MMCs). They also studied over viewing previous literatures that, composites, especially MMCs, have shown generally a wide range of deduction of at least 15 - 25% over metal counterparts and a less important functioning as well as persistence cost.

Since the record of the applicable life of composite structures is becoming obtainable, it can be supposed that they should be resilient, preserve dimensional stability, and defend against fatigue loading and easily maintained and repaired. Composites will prolong to find areas of new applications, but the huge development in the market for these equipments will involve less pricey dispensation methods and the viewpoint of recycling [17] will have to be solved [18].

2.2 Metal Matrix Composites

As researched by **Clyne T. W. *et. al*.**, [19] technically advanced materials with outstanding arrangement of engineering properties for enhanced performance and optimized serviceability are the requirements of the present and future advanced engineering applications. To achieve these properties, metal matrix composites (MMCs) have proved itself as an important class of engineering materials for the structural, wear, thermal, transportation and electrical applications. The combination of metallic matrix and reinforcement exerts phenomenon properties to produce a new class of material with an excellent arrangement of physical and mechanical properties which are absent in the individual constituent materials. The higher attention is being publicised towards metal matrix composites because of their outstanding engineering qualities like; higher wear resistant properties, higher fatigue strength, and enhanced corrosion resistance.

Rittner M & Evans A*et. al*. [20] discussed that Metal matrix composites (MMCs) are attracting substantial consideration because of their capability to adjust their physical, mechanical, and tribological properties for a specified application. [21] The prospect of manufacturing near dimensional requirement using conservative methods makes metal matrix composites more outstanding, even from the point of view of fabricating components. However, the increased cost of the currently accessible metal matrix composites are proving as a major obstacle in their extensive use.

S.Ilo*et. al*. [22] studied that, to accomplish a material having advanced physical, mechanical and tribological properties, composite materials are being extensively used. These materials are acknowledged due to their specifically tailored properties accomplished by combining two or more properties. Among various composite materials, researched, studied & implemented, metal matrix composites have been broadly studied, for their extensive applications in a range of engineering fields. Where ceramic particles such as SiC, Al2O3, TiN, and Graphite, etc. and various material can be added [23].

Metal matrix composites (MMCs) which are based upon pure aluminium and its alloys can be well thought-out for structural applications to provide improved physical, mechanical and tribological properties, in comparison to unreinforced aluminium. [24 – 27]The metal matrix composites (MMCs) consists of reinforcing materials and metal matrices such as aluminium, titanium, steel to obtain new materials or composites with good mechanical properties such as high stiffness, wear and temperature resistance. In recent years, SiC- Al MMCs have received significant attention and their fabrication techniques have been the major interest, which affect the mechanical properties of the composites. [28]

2.3 Fabrication Methods of Metal Matrix Composites

As per **Hashim *et al*.,** [28] fabrication techniques mostly affect the microstructure, distribution of the reinforcing materials and internal bond circumstance linking reinforcing phase and matrix. These techniques has to make sure the consistent allocation of the reinforcing constituent in the matrix and to position a strong bond between matrix and reinforcing material, and to obtain most favourable properties. A relative research of several fabrication routes for metal matrix composites is given in Table 2.1.

2.3.1 Why Aluminium Matrix selection

Aluminium MMCs provide superiorly significant arrangement of properties or set of properties, in such a method that these days no existing conventional material can present. Looking at the past, Aluminium MMCs is tested and applied in several structural, non-structural and purposeful applications in diverse engineering sectors. The major factors for the

Table 2.1 Comparative Study of various fabrication routes of MMCs

Route	**Scope of shape & size**	**Yielding**	**Mass Fraction**	**Injury to fillers**	**expenditure**
Powder metallurgy	extensive range, restricted size	High	-	Reinforcement fracture	Moderate
Squeeze casting	Limited by preform shape (up to 2cm Height)	small	just before 0.45	Severe	Moderate
Spray casting	Limited shape, large size	Medium	0.3 to 0.7	-	High
Mechanical stirring	Not limited by size	Medium	0.4 to 0.7	Little Damage	Moderate
Electro magnetic stirring	Not limited by size	High	0.5 to 0.8	No Damage	Moderate

employment of Aluminium MMCs in these fields are due to presentation, profitable and ecological benefits. The main benefits of Aluminium MMCs in automobile and aerospace sectors are due to lesser fuel consumption, quiet and minor harmful emissions. With growing rigorous environmental convention and importance on the enhanced fuel economy, application of Aluminium MMCs in these sectors is going to be predictable and desirable in the coming years [29]. Aluminium matrix composites has 30% times higher coefficient of friction compared to cast iron and it has better wear properties [30]

Due to its low density, exceptional tribological properties and specific strength, aluminium has been employed as a choice metal in many fields, such as in the car industry, railway and aeronautical sectors. A large part of the aluminium is used in the alloy states, containing various alloying elements [31]

2.4. Cenospheres as Reinforcements

Ngu L. *et al.* [32] studied about the fly ash cenosphere obtained from various Thermal Power Stations. Cenosphere particles are spherical in existence and almost 70% of cenosphere lies in the range between 40 and 155μm. They found both single-ring and network like structures in the samples. Single-ring like arrangements was the mainstream percentages than that of network like arrangements. The little spherical shaped fillers contain prominent percentages of SiO_2/Al $_2O_3$proportion than that of larger spherical cenosphere. The wall thickness to diameter ratio of the little spherical particle falls in between an upper boundary of 10.5% and lower boundary of 2.5%. They revealed that large size cenosphere has minor SiO_2/Al_2O_3 value.

Alcala J.F.C. [33] researched on the procedures and conditions of cenospheres obtained from thermal power plants. About 17% cenosphere was recovered from fly ash. The cenosphere experimentally found in the process revealed huge spherical fraction. They observed that they have empty space and occasionally the greater cenosphere was packed with smaller diameter cenosphere particle.

In the past decades, the exercise of fly ash as a strengthening material in Al alloys has been found to be advantageous from both environmental and economic points of view due to its availability as a economic industrial waste material [34]

In a research conducted by **Ramachandra et al.** [35] on the mechanical behaviour of Si / Fly-ash filled aluminium matrix composites, revealed that an amplification in the weight fraction of fly ash fillers proved in an elevation hardness and wear resistance. Whereas the compactness falls as the weight fraction of fly – ash elevates.

It has been observed that hollow spherical cenosphere particles in aluminium matrix provide outstanding wear resistance in both dry and lubricating conditions [36]. Because of spherical nature of these particles, these particles may not cause wear to the counter surface or the implant.

Cenospheres as filler in aluminium casting diminishes cost, decreases density and increases hardness, stiffness, wear and abrasion resistance [37, 38]. The presence of cenosphere increases the damping capacity and coefficient of friction, making them suitable in industries like automotive, aerospace etc. [39-42]

2.5. Wear Behaviour

Al-Rubaie et al. [43] observed the abrasive wear characteristics of Aluminium-SiC MMC prepared by varying the weight fraction of SiC reinforcement between 5% - 20% and particle size 10, 27 and 43 µm. Thus a varied range of abrasive study was conducted and the results showed that wear rates increases with increase in abrasive particle size but decreases with increase in volume percentage.

Another abrasive wear test was conducted by **Ahlatci *et al.*** [44], for varying particle size of Al_2O_3 abrasive particle. They concluded that with increase in particle size of $Al_2O_3$the wear rate increased.

Wear study of Aluminium-Mg-Cu toughened with SiC particle were studied by **Hassan *et al.*** [45] The comparative study of alloy and alloy reinforced with SiC suggested that wear resistant property of the alloy increased considerably with addition of SiC particle.

Straffelini *et al.* [46] studied the consequence of practical load applied and temperature over the wear behaviour of the samples they prepared and established that with increasing load the contact temperature increases beyond 1500º C, which elevates the wear rate of the material

R. N. Rao and S. Das [47] measured the consequence of sliding distance on the wear behaviour on Al-SiC along with reported that, wear rates increases with increase in load and sliding speed while wear resistance improves with heat treatment.

Axen*et al*. [48] Studied the abrasion resistance of alumina fiber reinforced aluminium using a pin on drum abrasion wear tester. The researchers fabricated the composites by hot liquid infiltration process. They finished with the conclusion that reinforcements of fiber significantly improve the abrasion resistance in milder abrasive situations, i.e., small and soft abrasives and low applied loads. However, in severe abrasive situations, the abrasion resistance of the composites was equal to or, in some cases, even lower than the unreinforced materials.

2.6 Powder Metallurgy

To fabricate components from the basic powder form can be done by the Powder Metallurgy process. The process of casting of metals came into the technical field long ago, but this technique had its limitations, due to the problem of melting them before casting because of their high melting point. Here comes powder metallurgy technique to be considered in the field of engineering. This route made it possible to produce the components inexpensively, and at present, this technique is occupying a significant position in the metal working process. The statistics of powder metallurgy material products are escalating day by day including tungsten filaments of lamps, aircraft wings, Self lubricated bearings, carbide cutting tools etc.

2.6.1 Basic Steps of the Process

Among all the diverse processing routes, powder metallurgy (P/M) route is one of the significant one for the fabrication of metal matrix composites. Significant benefits of powder metallurgy (P/M) route in comparison to other metallurgical routes consists of the regular circulation of reinforcing fillers surrounded by the matrix and a smaller amount of depreciation because of lesser working temperatures. Powder metallurgy (P/M) route for manufacturing powder filled MMCs consists of some basic steps which include the blending of a powders of matrix along with reinforcing fillers, technically followed by hot or cold compacting and sintering. Powder metallurgy (P/M) technique can basically and practically be applied to almost any matter that can be processed into powder [49].

Fabrication of components by powder metallurgy technique can be broadly classified into following, stepwise:

(a) Powder preparation
(b) Powder mixing/blending
(c) Compaction
(d) Sintering
(e) Finishing operations

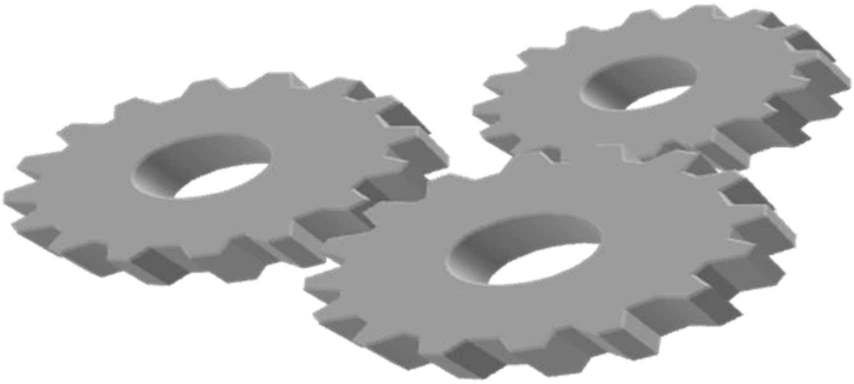
The sintering temperature and the time taken to sinter are depicted in Table. 2.2.

Table 2.2 Sintering time &Temperatures of various Metal Powders

Powder type	*Sintering temperature* (°C)	*Time to Sinter*
Al Alloys and pure Al	360-580	18 hrs.
Cu, Brass & Bronze	650-850	20 min.
Iron	1000-1250	20 min.
Tungsten Carbide	1460	15-45 min

To fabricate powder filled metal matrix composite, Powder metallurgy (PM) routes are being used comprehensively. Using these routes, the matrix, as well as, the strengthening part is used in the powder form. Solid state mixing is done of the powders thoroughly; then they are manufactured into billets using various methods of compaction followed by sintering of the products. This method can lead to several advantages. Homogeneity of the mixture is the main factor, which is well guarded. The consequential composite billets presents all the advantages of the speedily solidified metal powders, and the components are produced in near net shape dimensions [50, 51].

Powders processing is used to produce properties which are not achievable through monolithic engineering techniques or to fabricate parts to near dimensional accuracy. Aluminium matrix composites fabricated through powder metallurgy route is beneficial for the discussed two reasons. Powder metallurgy is currently used to produce mega strength and creep resistant materials beyond the possible levels by monolithic metallurgy techniques. In addition with an enhanced alloying potential which provides novel possibilities for material design, this route has guided to the improvement of materials with unparalleled tribological properties.[52]



MATERIALS AND METHODS

3.1 INTRODUCTION

Powder Metallurgy (PM route):

To fabricate a metal matrix composite, as per the recent engineering trend, a superior blendable route should be adapted. In this aspect, Powder Metallurgy route is considered as the most favourable route. The main advantageous point is to fabricate the component at low processing temperature in comparison to other melting techniques, which prevents the physical or chemical interactions among the matrix and the strengthening phase. Here, by adapting this technique, a good distribution of filler particles is achieved [53]

Rajesh Purohit et. al. [54] Al-SiC_p composites with 5 to 30 weight % of SiC_p were fabricated using powder metallurgy process. The density, porosity, hardness, compressive strength and indirect tensile strength of Al-SiC_p composites were found to increase with increase in the wt. % of SiC_p from 5 to 30 weight percent. Mechanical alloying of powders resulted in improvement in hardness and compressive strength of Al –SiCp composites with 5 to 30 weight % of SiCp.

3.2 Experimental Aspects

3.2.1 Raw Materials Used

The materials used in this investigational work are listed below:

1. Fillers (Cenospheres)
2. Aluminium Powder

Cenospheres:

Cenospheres (C/S) are basically thin-walled hollow spherical particles with relative density ranging between 0.6 - 0.8 gm/cm^3. They are floated on water and are recovered from the float up, of ash disposal lagoons and are similar chemical composition as that of fly ash. Cenosphere are used in various industries due to their unique combination of spherical shape, high compression, low specific gravity, good thermal and acoustical insulation properties and inertness to acids and alkalis.

The characteristics and properties of cenospheres taken into study are shown in **Table 3.1** & **3.2**. Cenospheres used in this study is shown in the **Fig.** 3.1

The central pores contain typically 70% CO_2 and 30% NO_2 in gaseous form (generally inert gases).

Table 3.1 Characteristics of cenospheres (c/s)

Size	1-550 microns
pH in Water	6.0 - 8.0
Bulk Density	350-500 Kgs/CBM
Specific Gravity	0.6 - 0.8
Compressive Strength	1550 - 3100 Psi
Melting Point	> 1150ºC
Shape	Spherical
Moisture	0.45% Max
Sinkers	4% Max

Table 3.2 Properties of Cenospheres (c/s) used

Grade	CS300
Size	50 – 150µm
Density	0.6 gm / cm^3

Fig. 3.1cenospheres (c/s)

3.2.1.1 XRD study of cenospheres:

XRD is a useful method to characterize the crystalline structure, phase composition, orientation in the sample and crystallographic structure of semi-crystalline material such as ceramic rich cenosphere powder.

A Philips X-Ray diffractometer employing CuK_{α} (λ=1.54A^0) radiation and a graphite monochromator, with a current flow of 20A and voltage of 30V was used with a diffraction intensity in the range of 20º-80º (2θ-angle range).

The crystallinity was evaluated by applying the peak-area integration method in the range of 2θ = (20º-80º) by applying an amorphous scattering curve that was realized by experimental and theoretical experiences.

The phase composition of inward bound fly ash cenosphere are metal oxide and non- metal oxide and the main phase composition are α-SiO_2 and $3Al_2$ $O_3.2SiO_2$.

The X-Ray diffractograms of cenosphere powder is shown in **Fig.** 3.2:

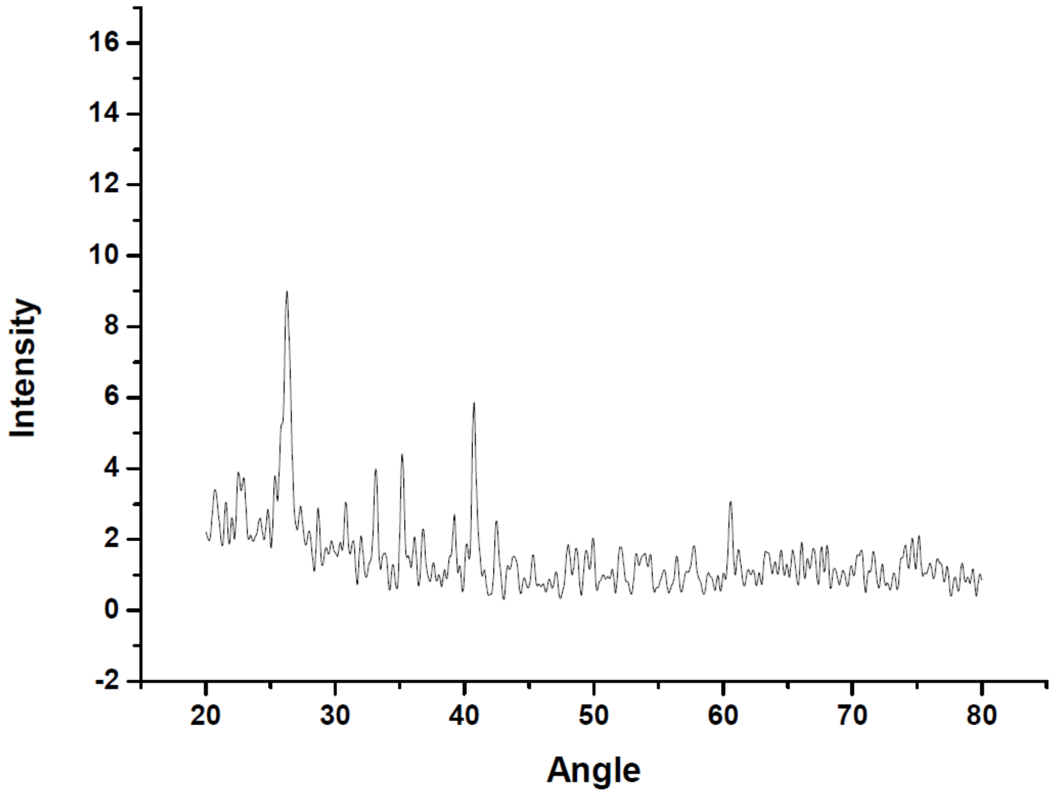


Fig. 3.2 X – Ray Diffractograms of Cenospheres (c/s)

It was observed that the major crystalline peak of the profile occurred at around 2θ=26.294° for amorphous cenosphere powder.

The crystallinity index(I_c) of cenosphere powders were calculated by using equation below.

$$I_c = \left[\frac{I_{crystalline} - I_{amorphous}}{I_{crystalline}}\right]$$

Where: $I_{crystalline}$= Maximum intensity of diffraction of the sharp lattice peak at angle 2θ between 20° and 30°

$I_{amorphous}$= Minimum intensity of diffraction of the smooth lattice peak taken at angle 2θ between 70° and 80°

3.2.1.2 EDX analysis

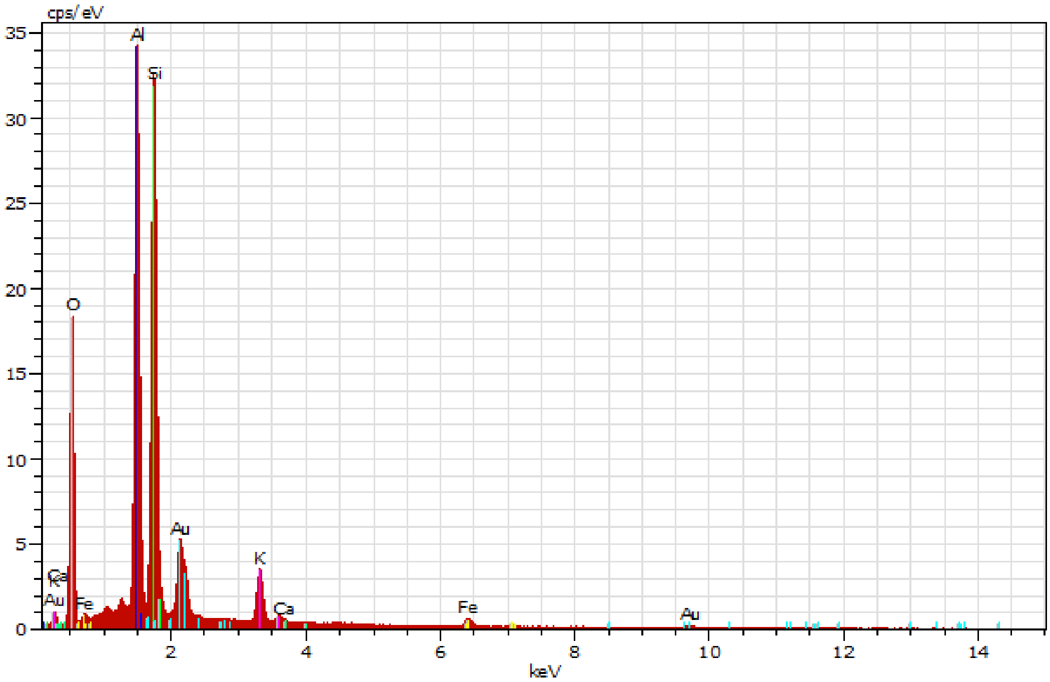
Figure 3.3 resembles the EDX spectrum of cenosphere particles showing the compositional analysis of cenospheres.

Aluminium (Fine Powder)

Commercially pure aluminium of IE–07 grades, supplied by Loba Chemie Pvt. Ltd., Mumbai of Maharashtra, **Fig. 3.4**, was used for experimental purpose. The compositions & physical properties are presented in **Table-3.3**and **3.4**.

Table 3.3 Composition of Aluminium Powder

Sl. No.	Composition	Weight Percentage
1.	Al	98.0%
2.	Impurities, insoluble in Dil. HCl	0.005%
3.	Iron (Fe)	0.1%
4.	Manganese (Mn)	0.02%
5.	Titanium (Ti)	0.03%
6.	Nitrogen contents (N)	0.001%
7.	Copper (Cu)	0.02%
8.	Silicon (Si)	0.1%



Spectrum: Sample 1 536

El	AN	Series	Net	unn.C [wt.%]	norm.C [wt.%]	Atom.C [at.%]	Error (1 Sigma) [wt.%]
O	8	K-series	68116	22.15	38.12	52.89	2.58
Si	14	K-series	165646	16.86	29.01	22.93	0.73
Al	13	K-series	158236	13.79	23.73	19.53	0.66
K	19	K-series	21854	3.32	5.71	3.24	0.13
Fe	26	K-series	4168	1.83	3.16	1.25	0.09
Ca	20	K-series	881	0.16	0.27	0.15	0.03
Au	79	M-series	41551	0.00	0.00	0.00	0.00
			Total:	58.12	100.00	100.00	

Fig. 3.3 EDX spectrum of Cenospheres

Table 3.4 Physical Properties of Aluminium

Purity	98%
Grade	extra pure
Physical State (20ºC)	solid
Colour	Grey
Density	2.7 gm/cc
Hardness	40.8 VHN
Tensile strength	67 MPa
Mol. Weight	26.98
Melting Point	660.37ºC
Auto ignition Temperature	760ºC
Boiling Point	2327ºC

Fig. 3.4 Aluminium Powder used in present work.

3.3ExperimentalMethodology

3.3.1 Preparation of the test specimens

3.3.1.1 Mixing of Powders

Blending or mixing is a procedure of thorough combination of various powders or particles which are of same or dissimilar combinations. For the consistency of the product developed, appropriate powder blending or mixing is vital. Different quantities of cenospheres were supplementary added to aluminium fine powder to set up the composite samples with 10, 20 &

30 weight percentage of cenospheres. For this to begin with, the cenospheres and aluminium powder were added together as per the weight percentage desired and then dried at a temperature of 100^0C to eliminate moisture. Then prepared mixtures of aluminium with 10 to 30 weight percent of cenosphere (c/s) fillers were filled in plastic bottles and placed in the Abrasion Tester, Model No. PEI 300 for mechanical mixing, as shown in the **Fig.** 3.5 in the ambient atmosphere. The whole process took 18 Hrs. The steel balls taken in an average of six were used as additional mixing supplementary.

Fig. 3.5 Abrasion Tester

3.3.1.2 Cold Compaction

Approximately 4 gm. weight of sample was taken and one or two drops of water were added to it to give some extra requisite property.

Then the die was cleaned with cotton soaked in acetone, to remove all the dust from the inside cavity of the die and outside surface of the punch, as shown in the **Fig.** 3.6. Then proper greasing was done to avoid sticking. Finally cenosphere and Aluminium powder mixture prepared earlier was poured inside carefully by using a paper funnel. While stuffing the powders, minor shaking was done to lodge the most achievable amount of powders. Then the die arrangement was subjected to hydraulic press, as shown in the **Fig.** 3.7.Load of 4 tons was applied gradually. Then the load was dwelled for 5 min at 4 ton so that there is ideal bonding among the powders.

Samples were ejected from the die as per the same process. The samples were prepared by the above process

These are some of the images of the instrumental set up.

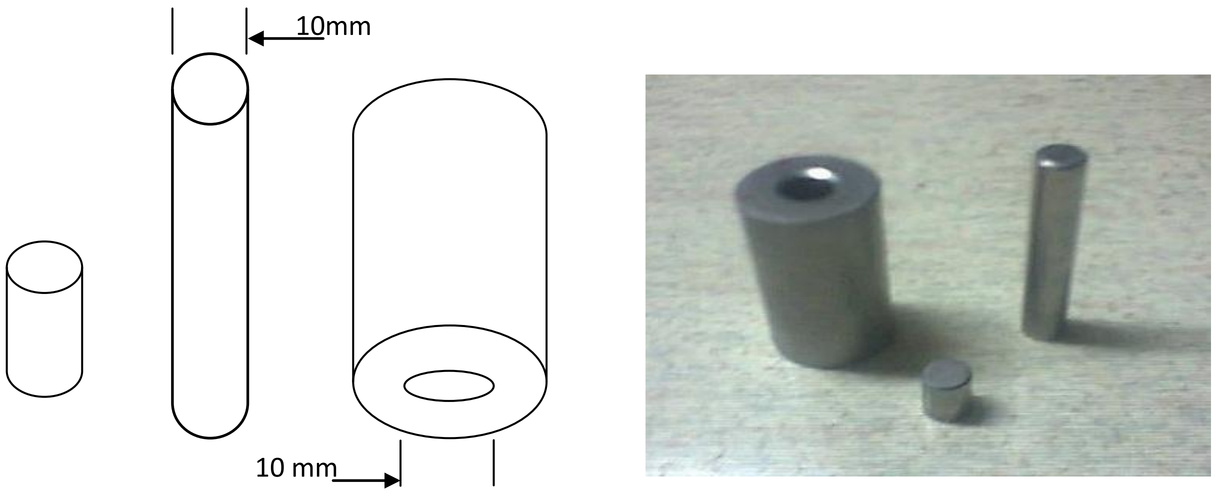


Fig. 3.6 Die Used for Cold Compaction

Fig. 3.7 Hydraulic Press used for Cold Compaction

3.3.1.3 Sintering

The prepared cold green compacts of cenosphere filled aluminium matrix composites were sintered in an electric furnace at 500ºC for a period of 300 minutes as shown in figure 3.8.

Normally ductile metals are sintered at 0.6 to0.8 times of the melting point; this method is applied to decrease the void content and to increase the shrinkage among the powders. Also the number of bonds among the particles also increases. They also provide spherical pores among the particles. After the 300 minutes of sintering, it was sanctioned to cool to room temperature in the furnace itself.

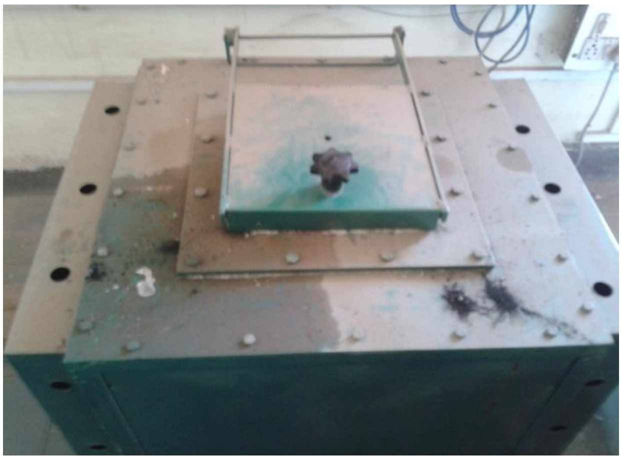


Fig. 3.8 Furnace used for sintering process

After the whole process, the prepared sintered compacts are shown in the fig. 3.9

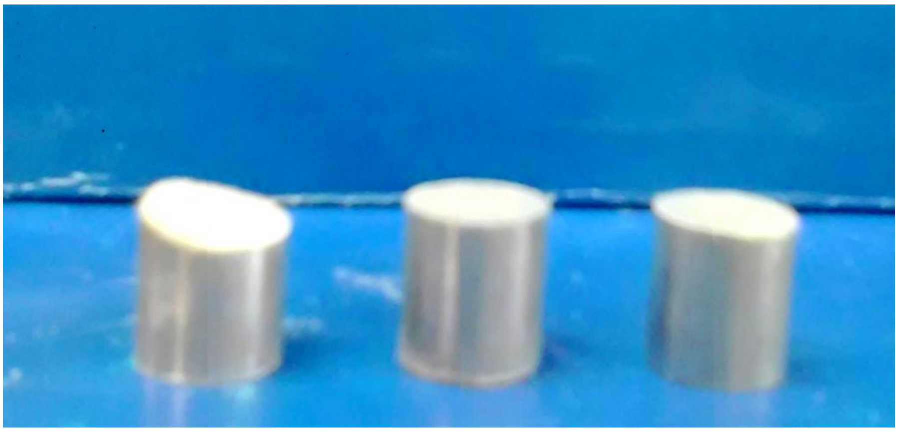


Fig. 3.9 Prepared Cenosphere filled Al matrix composites

3.4 Test Procedure

The following tests were conducted on the samples:

(i)Testing of mechanical properties

a. Density measurement

b. Hardness test

(ii)Testing of tribological properties

a. Dry sliding wear test

3.4.1 Measurement of Density and void content

Density is the physical property that reflects the features of composites. In a composite, the magnitude of the matrix and reinforcement ratio (volume / weight) are proposed either as the weight fraction (*w*), which is relevant to fabrication, or the volume fraction (*v*), which is commonly used in property calculations.

Theoretically, density is determined by 'Law of Mixtures' expressed in equation – 1. Where, 'm' stands for matrix and 'r' for reinforcing filler:

$$X_c = X_m w_m + X_r w_r \tag{1}$$

Experimentally, the density of a composite was found by displacement methods [55] using a physical balance and a pycnometer, as per ASTM: D 792-66 test method, as per the equation - 2. Further, the density can also be calculated from porosity and apparent density values (sample mass and dimensions) [56]

$$(\rho_{act}) = \frac{w_o}{(w_o) + (w_a - w_b)} \tag{2}$$

Where "ρ_{act}" represents specific gravity of the composite,

"w_0" Represents the weight of the sample; "w_a" represents the weight of the bottle + kerosene,

"w_b" represents the weight of the bottle + kerosene + sample,

Density of composite $=\rho_{act}$ × density of kerosene**.**

The void fraction of composite specimen was been determined as per ASTM D-2734-70 standard process.

3.4.2 Hardness test

The resistance to notch or scrape is determined as hardness. Hardness can be measured by various hardness testing machines like, Brinell's, Rockwell's and Vickers hardness testers. Theoretically, the rule of mixture was applied to figure out the hardness of the composite, given by equation-3:–

$$H_c = H_m w_m + H_r w_r \tag{3}$$

Where *w* and H stand for weight fraction and hardness respectively for composites [57] helps to determine the approximate hardness values.

In this investigation, Vickers hardness tester was used to find out the hardness value of the fabricated composites. A force of 3Kgf was applied for 5 seconds for the indentation.

3.4.3Dry Sliding Wear Test

This test was done with the help of a Pin-on-Disc apparatus. This is one the most versatile apparatus, especially designed to investigate the sliding wear behaviour of a component. Here, in this test, the parameters like, normal load applied, sliding speed and distance found from the track diameter, can be varied. In this test, the test specimen is stable and the disc is rotating, to provide sliding wear. They move in the opposite direction, relative to each other.

3.4.3.1 Test Procedure

The specimen is tested as per the testing standard ASTM G99 to study the abrasive wear. A schematic representation of the test configuration is shown in **Fig.** 3.10.

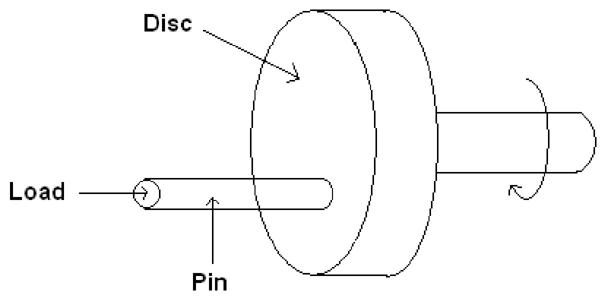


Fig. 3.10 Schematic Representation of PIN – on – Disc abrasion test

Before starting the test, the specimen is weighed. The testing specimen is held by the holder provided. The rotating disc was mounted with 100 grade abrasive paper. To fix the abrasive paper on the disc, Araldite was applied to the disc. The normal load was applied as per the parameters taken, and the disc containing the test specimen was rotated. The speed of the disc or motor RPM can be varied through the controller and interval of time can be set by the help of timer provided at the control panel. The weight if the test specimen was weighed before and after each test in a physical weight balance, of an accuracy of 0.001 g, before and after each test, to determine the weight loss, to help to find out the abrasive loss. Care was taken to clean the test specimen to clean the test surface with woollen cloth soaked in acetone, so as to remove all the debris present on the surface.

Dry sliding wear test was carried out on a pin-on-disc wear testing machine (As per ASTM G-99 standard) delivered by Magnum Engineers, Bangalore. The schematic design is shown in the fig.3.11, and the test setup is shown the fig. Figure-3.12 (a, b).

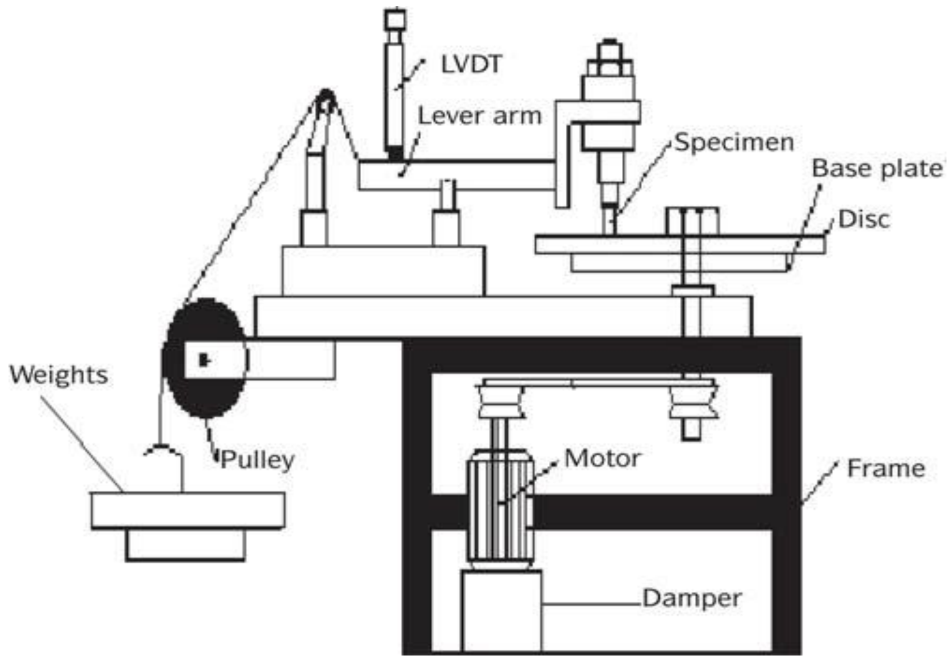


Fig. 3.11 Design of Pin-on-Disc test apparatus

Fig.3.12 (a) Test Apparatus

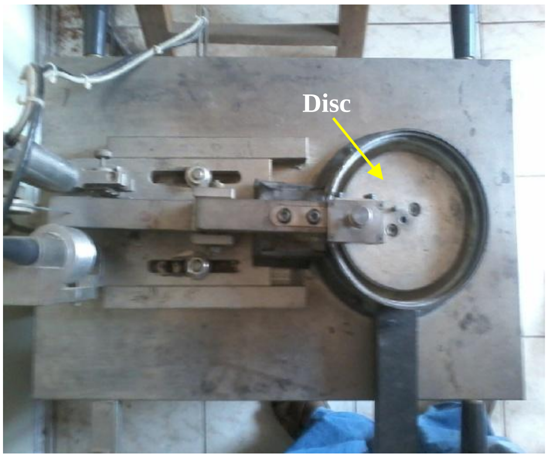


Fig. 3.12 (b) Specimen loading set up

The test parameters under which the experiment was carried out is given in Table-3.5

Table 3.5 Pin – on – Disc Test Parameters

Test parameters	Units	Values
Weight fraction of c/s	%	0,10,20,30
Load (F_n)	N	5,7.5,10,
Sliding Velocity (v)	m/s	1.0472,1.5708,2.0944
Track radius	mm	50
Temperature	$\Theta^{\circ C}$	Ambient

3.5Calculation for Wear:

Wear rate is determined by calculating the weight loss of the specimen after each test. The weight loss calculated by following equation

$$(\Delta w) = (w_a - w_b) \text{ gm} \qquad (4)$$

Where Δw is the weight loss in gm and w_a and w_b are the weight of the sample after and before the abrasion test in gm.

The abrasive wear rate W which relates to the weight loss to sliding distance (S_d) can be calculated by using the following formula:

$$W = \frac{\Delta w}{(S_d \times \rho)} \quad (5)$$

Where:

W - Wear rate in *m*^{3} */ m*,

P - Density of the composite in *gm/cm*^{3},

Δw - Weight loss in *gm*, and;

S_d - Sliding distance in *m*.

For abrasive wear behaviour of composites, the specific wear rate (W_s) is taken into consideration. This is found out as per the following equation:

$$W_s = \frac{W}{F_n} \quad (6)$$

Usually Volumetric wear rate is the inverse of specific wear rate expressed as follows:

$$W_s = \frac{W_v}{(v_s \times F_n)} \quad (7)$$

Where:

W_s - Specific wear rate, m^3/ nm

W_v - Volumetric wear rate, m^3/sec

v_s - Sliding velocity, in m/sec

The friction force was recorded for each individual test and then the average was calculated to find the co-efficient of friction as per:

$$\mu = \frac{F_f}{F_n} \tag{8}$$

Where:

F_f - Average friction force, and,

F_n - Applied load in N.

3.6 Friction and Wear Test

Results of friction and wear test of different test samples at different test conditions and parameters are tabulated and presented in the following tables:

Table 3.6

Al + 0 wt% c/s **load – 5N** ρ **=2.7 × 10^6 g/cm^3**

RPM – 100 **Track Radius – 0.05m** v_s **=0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.74	3.629	0.111	4.35	0.871	300	0.1571	2.617	5.234	13.704
3.74	3.552	0.188	4.41	0.882	600	0.3142	2.216	4.432	11.605
3.74	3.508	0.232	4.21	0.842	900	0.4713	1.823	3.646	9.547
3.74	3.479	0.261	4.12	0.824	1200	0.6284	1.538	3.077	8.055
3.74	3.431	0.309	4.08	0.816	1500	0.7855	1.457	2.914	7.629

Table 3.7

Al + 0 wt% c/s **load – 5N** **$\rho = 2.7 \times 10^3$ g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.468	2.262	0.206	4.42	0.884	300	0.3142	2.42827	4.85654	25.4321
2.468	2.247	0.221	4.29	0.858	600	0.6284	1.30254	2.60509	13.642
2.468	2.229	0.239	4.36	0.872	900	0.9426	0.939089	1.87818	9.83539
2.468	2.172	0.296	4.31	0.862	1200	1.2568	0.872292	1.74458	9.1358
2.468	2.145	0.323	4.37	0.874	1500	1.571	7.61487	1.52297	7.97531

Table 3.8

Al + 0 wt% c/s **load – 5N** **$\rho = 2.7 \times 10^3$ g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.318	1.978	0.340	4.59	0.918	300	0.471	26.736	5.347	41.975
2.318	1.879	0.439	4.38	0.876	600	0.942	17.260	3.452	27.098
2.318	1.854	0.464	4.52	0.904	900	1.413	12.162	2.432	19.094
2.318	1.761	0.557	4.43	0.886	1200	1.884	10.949	2.189	17.191
2.318	1.687	0.631	4.47	0.894	1500	2.355	09.924	1.985	15.580

Table 3.9

Al + 0 wt% c/s **load – 7.5N** **ρ = 2.7 × 10^3 g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.624	2.506	0.118	5.579	0.744	300	0.1571	27.819	3.709	14.568
2.624	2.438	0.186	5.452	0.727	600	0.3142	21.925	2.923	11.481
2.624	2.389	0.235	5.349	0.713	900	0.4713	18.467	2.462	09.670
2.624	2.351	0.273	5.476	0.730	1200	0.6284	16.090	2.145	08.426
2.624	2.309	0.315	5.408	0.721	1500	0.7855	14.852	1.9803	07.778

Table 3.10

Al + 0 wt% c/s **load – 7.5N** **ρ = 2.7 × 10^3 g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.437	2.189	0.248	5.591	0.745	300	0.3142	29.233	3.898	30.617
2.437	2.062	0.375	5.467	0.728	600	0.6284	22.102	2.947	23.148
2.437	1.963	0.474	5.35	0.713	900	0.9426	18.624	2.483	19.506
2.437	1.893	0.544	5.54	0.738	1200	1.2568	16.031	2.137	16.790
2.437	1.813	0.624	5.41	0.721	1500	1.571	14.711	1.961	15.407

Table 3.11

Al + 0 wt% c/s **load – 7.5N** **$\rho = 2.71 \times 10^3$ g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.511	3.132	0.379	6.23	0.831	300	0.471	29.802	3.973	46.790
3.511	2.959	0.552	5.98	0.797	600	0.942	21.703	2.893	34.074
3.511	2.762	0.749	6.192	0.825	900	1.413	19.632	2.617	30.823
3.511	2.663	0.848	5.917	0.788	1200	1.884	16.670	2.223	26.172
3.511	2.541	0.970	6.051	0.806	1500	2.355	15.255	2.034	23.951

Table 3.12

Al + 0 wt% c/s **load – 10N** **$\rho = 2.71 \times 10^3$ g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.393	3.247	0.146	7.862	0.786	300	0.1571	34.420	3.442	18.024
3.393	3.178	0.215	7.724	0.772	600	0.3142	25.343	2.534	13.271
3.393	3.139	0.254	7.891	0.789	900	0.4713	19.961	1.996	10.452
3.393	3.119	0.274	7.698	0.769	1200	0.6284	16.149	1.615	08.456
3.393	3.071	0.322	7.659	0.765	1500	0.7855	15.182	1.518	07.950

Table 3.13

Al + 0 wt% c/s **load – 10N** **$\rho = 2.71 \times 10^3$ g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.714	2.421	0.293	8.176	0.817	300	0.3142	34.538	3.454	36.173
2.714	2.305	0.409	8.082	0.808	600	0.6284	24.106	2.411	25.247
2.714	2.227	0.487	8.175	0.817	900	0.9426	19.135	1.913	20.041
2.714	2.123	0.591	7.986	0.798	1200	1.2568	17.416	1.742	18.241
2.714	2.025	0.689	8.017	0.801	1500	1.571	16.243	1.624	17.012

Table 3.14

Al + 0 wt% c/s **load – 10N** **$\rho = 2.71 \times 10^3$ g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.528	2.087	0.441	8.26	0.826	300	0.471	34.678	3.468	54.444
2.528	1.907	0.621	8.35	0.835	600	0.942	24.416	2.442	38.333
2.528	1.689	0.839	8.39	0.839	900	1.413	21.992	2.199	34.527
2.528	1.589	0.939	7.87	0.787	1200	1.884	18.459	1.846	28.981
2.528	1.490	1.038	7.92	0.792	1500	2.355	16.325	1.632	25.629

Table 3.15

Al + 10 wt% c/s **load – 5N** **ρ = 2.348 × 10^6 g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.86	3.821	0.039	4.75	0.95	300	0.1571	10.573	2.114	5.536
3.86	3.791	0.069	4.72	0.944	600	0.3142	09.353	1.871	4.898
3.86	3.771	0.089	4.72	0.944	900	0.4713	08.042	1.608	4.211
3.86	3.746	0.114	4.67	0.934	1200	0.6284	07.726	1.545	4.046
3.86	3.728	0.132	4.61	0.922	1500	0.7855	07.157	1.431	3.748

Table 3.16

Al + 10 wt% c/s **load – 5N** **ρ = 2.348 × 10^6 g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.863	3.781	0.082	4.14	0.828	300	0.3142	11.112	2.222	11.897
3.863	3.711	0.152	3.62	0.724	600	0.6284	10.299	2.059	11.026
3.863	3.671	0.192	3.61	0.722	900	0.9426	08.673	1.734	09.285
3.863	3.628	0.235	3.77	0.754	1200	1.2568	07.961	1.592	08.524
3.863	3.592	0.271	3.83	0.766	1500	1.571	07.345	1.469	07.863

Table 3.17

Al + 10 wt% c/s **load – 5N** **$\rho = 2.348 \times 10^6$ g/cm^3**

RPM – 300 **Track Radius – 0.05 m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.535	3.379	0.156	3.75	0.75	300	0.471	14.093	2.818	22.146
3.535	3.287	0.248	3.92	0.784	600	0.942	11.202	2.240	17.603
3.535	3.215	0.32	4.12	0.824	900	1.413	09.636	1.927	15.143
3.535	3.112	0.423	3.72	0.744	1200	1.884	09.553	1.911	15.012
3.535	3.021	0.514	3.63	0.726	1500	2.355	09.287	1.857	14.594

Table 3.18

Al + 10 wt% c/s **load – 7.5N** **$\rho = 2.348 \times 10^6$ g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.573	2.519	0.054	6.1	0.813	300	0.1571	14.639	1.952	7.666
2.573	2.495	0.078	6.2	0.827	600	0.3142	10.573	1.409	5.536
2.573	2.461	0.112	5.8	0.773	900	0.4713	10.121	1.349	5.301
2.573	2.426	0.147	5.6	0.747	1200	0.6284	09.963	1.328	5.217
2.573	2.407	0.166	5.5	0.743	1500	0.7855	09.001	1.201	4.713

Table 3.19

Al + 10 wt% c/s **load – 7.5N** **$\rho = 2.348 \times 10^6$ g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
4.08	3.931	0.149	3.16	0.421	300	0.3142	20.196	2.692	21.152
4.08	3.912	0.168	4.4	0.587	600	0.6284	11.386	1.518	11.925
4.08	3.899	0.181	4.9	0.653	900	0.9426	08.178	1.090	08.565
4.08	3.885	0.195	4.5	0.601	1200	1.2568	06.608	0.881	06.921
4.08	3.871	0.209	3.9	0.520	1500	1.571	05.665	0.755	05.934

Table 3.20

Al + 10 wt% c/s **load – 7.5N** **$\rho = 2.348 \times 10^6$ g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.875	2.621	0.254	4.725	0.630	300	0.471	22.967	3.062	36.059
2.875	2.579	0.296	5.21	0.695	600	0.942	13.383	1.784	21.011
2.875	2.491	0.384	5.35	0.713	900	1.413	11.574	1.543	18.171
2.875	2.431	0.444	5.64	0.752	1200	1.884	10.037	1.338	15.758
2.875	2.412	0.463	5.15	0.687	1500	2.355	08.373	1.116	13.146

Table 3.21

Al + 10 wt% c/s **load – 10N** **ρ = 2.348 × 10^6 g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	S_d×10^3 (m)	W ×10^{-11} (m^3/m)	W_s× 10^{-11} (m^3/Nm)	W_v×10^{-11} (m^3/sec)
4.108	4.030	0.078	5.8	0.58	300	0.1571	21.145	2.114	11.073
4.108	3.989	0.119	6.4	0.64	600	0.3142	16.130	1.613	08.446
4.108	3.960	0.148	6.2	0.62	900	0.4713	13.374	1.337	07.003
4.108	3.926	0.182	5.9	0.59	1200	0.6284	12.335	1.233	06.459
4.108	3.896	0.212	6.1	0.61	1500	0.7855	11.494	1.149	06.019

Table 3.22

Al + 10 wt% c/s **load – 10N** **ρ = 2.348 × 10^6 g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	S_d×10^3 (m)	W ×10^{-11} (m^3/m)	W_s× 10^{-11} (m^3/Nm)	W_v×10^{-11} (m^3/sec)
3.492	3.331	0.161	8.3	0.83	300	0.3142	21.823	2.182	22.856
3.492	3.216	0.276	7.65	0.765	600	0.6284	18.705	1.871	19.591
3.492	3.187	0.305	6.78	0.68	900	0.9426	13.781	1.378	14.433
3.492	3.126	0.366	7.52	0.752	1200	1.2568	12.403	1.241	12.989
3.492	3.072	0.423	6.85	0.685	1500	1.5711	11.386	1.138	11.925

Table 3.23

Al + 10 wt% c/s **load – 10N** **ρ = 2.348 × 10^6 g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.241	2.991	0.25	8.45	0.845	300	0.471	22.606	2.261	35.491
3.241	2.847	0.394	7.58	0.758	600	0.942	17.813	1.781	27.967
3.241	2.762	0.479	6.87	0.687	900	1.413	14.437	1.444	22.667
3.241	2.654	0.587	7.18	0.718	1200	1.884	13.269	1.327	20.833
3.241	2.587	0.654	6.23	0.623	1500	2.355	11.827	1.183	18.569

Table 3.24

Al + 20 wt% c/s **load – 5N** **ρ =2.176 × 10^6 g/cm**

^{3}RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W$\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.652	3.631	0.021	3.475	0.695	300	0.1571	6.141	1.228	3.217
3.652	3.616	0.036	2.821	0.564	600	0.3142	5.264	1.053	2.757
3.652	3.601	0.051	3.217	0.643	900	0.4713	4.972	9.943	2.605
3.652	3.587	0.065	3.179	0.636	1200	0.6284	4.753	0.951	2.489
3.652	3.571	0.081	2.945	0.589	1500	0.7855	4.737	0.947	2.482

Table 3.25

Al + 20 wt% c/s **load – 5N** ρ **=2.176 × 10^6 g/cm^3**

RPM – 200 **Track Radius – 0.05m** v_s **=1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.057	3.027	0.030	4.58	0.916	300	0.3142	4.387	0.877	4.595
3.057	3.009	0.048	3.62	0.724	600	0.6284	3.509	0.702	3.676
3.057	2.989	0.068	3.61	0.722	900	0.9426	3.314	0.663	3.472
3.057	2.968	0.089	3.76	0.752	1200	1.2568	3.253	0.651	3.408
3.057	2.957	0.100	3.83	0.765	1500	1.571	2.925	0.585	3.064

Table 3.26

Al + 20 wt% c/s **load – 5N** ρ **=2.176 × 10^6 g/cm^3**

RPM – 300 **Track Radius – 0.05m** v_s **=1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.783	2.716	0.067	3.40	0.682	300	0.471	6.531	1.306	10.263
2.783	2.679	0.104	2.85	0.571	600	0.942	5.069	1.014	07.965
2.783	2.659	0.124	3.38	0.676	900	1.413	4.029	0.805	06.332
2.783	2.624	0.159	3.32	0.664	1200	1.884	3.875	0.775	06.089
2.783	2.591	0.192	3.34	0.668	1500	2.355	3.743	0.748	05.882

Table 3.27

Al + 20 wt% c/s **load – 7.5N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.603	3.574	0.029	4.167	0.555	300	0.1571	8.483	1.131	4.442
3.603	3.564	0.039	3.275	0.436	600	0.3142	5.704	0.761	2.987
3.603	3.546	0.057	3.782	0.504	900	0.4713	5.558	0.741	2.911
3.603	3.532	0.071	3.685	0.491	1200	0.6284	5.192	0.692	2.719
3.603	3.516	0.087	3.672	0.489	1500	0.7855	5.089	0.678	2.665

Fig. 3.28

Al + 20 wt% c/s **load – 7.5N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 20 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.818	2.741	0.077	5.55	0.740	300	0.3142	11.262	1.502	11.795
2.818	2.719	0.099	4.10	0.547	600	0.6284	07.241	0.965	07.582
2.818	2.701	0.117	4.40	0.587	900	0.9426	05.704	0.761	05.974
2.818	2.689	0.129	4.38	0.584	1200	1.2568	04.716	0.628	04.941
2.818	2.662	0.156	4.16	0.555	1500	1.571	04.563	0.608	04.779

Fig 3.29

Al + 20 wt% c/s **load – 7.5N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.541	2.423	0.118	5.50	0.733	300	0.471	11.513	1.535	18.076
2.541	2.365	0.176	5.20	0.693	600	0.942	08.586	1.145	13.481
2.541	2.309	0.232	4.82	0.643	900	1.413	07.545	1.006	11.846
2.541	2.278	0.263	4.91	0.655	1200	1.884	06.415	0.855	10.072
2.541	2.249	0.292	4.85	0.647	1500	2.355	05.698	0.759	08.946

Fig 3.30

Al + 20 wt% c/s **load – 10N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.309	2.275	0.034	4.7	0.47	300	0.1571	9.945	0.994	5.208
2.309	2.248	0.061	4.3	0.43	600	0.3142	8.922	0.892	4.672
2.309	2.23	0.079	3.5	0.35	900	0.4713	7.703	0.770	4.034
2.309	2.219	0.09	4.2	0.42	1200	0.6284	6.581	0.658	3.446
2.309	2.209	0.1	3.9	0.39	1500	0.7855	5.850	0.585	3.064

Fig 3.31

Al + 20 wt% c/s **load – 10N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.028	2.949	0.079	4.93	0.492	300	0.3142	11.554	1.155	12.101
3.028	2.902	0.126	5.65	0.565	600	0.6284	09.214	0.921	09.651
3.028	2.857	0.171	4.67	0.467	900	0.9426	08.337	0.833	08.732
3.028	2.813	0.215	4.56	0.456	1200	1.2568	07.862	0.786	08.234
3.028	2.871	0.157	4.87	0.487	1500	1.571	04.592	0.459	04.811

Table 3.32

Al + 20 wt% c/s **load – 10N** **ρ =2.176 × 10^6 g/cm^3**

RPM – 300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.701	3.579	0.122	3.81	0.38	300	0.471	11.903	1.191	18.688
3.701	3.512	0.189	4.42	0.4425	600	0.942	9.221	0.922	14.476
3.701	3.458	0.243	4.41	0.4415	900	1.413	7.903	0.791	12.408
3.701	3.411	0.290	4.46	0.446	1200	1.884	7.073	0.707	11.106
3.701	3.382	0.319	3.85	0.385	1500	2.355	6.225	0.623	09.773

Table 3.33

Al + 30 wt% c/s **load – 5N** ρ **=1.89 × 10⁶ g/cm³**

RPM – 100 **Track Radius – 0.05m** v_s **=0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d\times10^3$ (m)	$W\times10^{-11}$ (m^3/m)	$W_s\times10^{-11}$ (m^3/Nm)	$W_v\times10^{-11}$ (m^3/sec)
3.95	3.899	0.051	3.48	0.696	300	0.1571	17.176	3.435	7.813
3.95	3.878	0.072	3.52	0.704	600	0.3142	12.124	2.425	5.515
3.95	3.871	0.079	3.32	0.664	900	0.4713	08.868	1.774	4.034
3.95	3.858	0.092	3.45	0.69	1200	0.6284	07.746	1.549	3.523
3.95	3.838	0.112	3.36	0.672	1500	0.7855	07.544	1.509	3.431

Table 3.34

Al + 30 wt% c/s **load – 5N** ρ **=1.89 × 10⁶ g/cm³**

RPM –200 **Track Radius – 0.05m** v_s **=1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d\times10^3$ (m)	$W\times10^{-11}$ (m^3/m)	$W_s\times10^{-11}$ (m^3/Nm)	$W_v\times10^{-11}$ (m^3/sec)
3.587	3.478	0.109	3.79	0.758	300	0.3142	18.355	3.671	19.224
3.587	3.455	0.132	3.65	0.73	600	0.6284	11.114	2.223	11.641
3.587	3.43	0.157	3.81	0.762	900	0.9426	08.813	1.762	09.229
3.587	3.392	0.195	3.76	0.752	1200	1.2568	08.209	1.642	08.598
3.587	3.366	0.221	3.74	0.748	1500	1.571	07.443	1.488	07.795

Table 3.35

Al + 30 wt% c/s **load – 5N** **ρ =1.89 × 10^6 g/cm^3**

RPM –300 **Track Radius – 0.05m** **v_s =1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.225	3.038	0.187	3.68	0.736	300	0.471	21.006	4.201	32.981
3.225	2.994	0.231	3.42	0.684	600	0.942	12.974	2.595	20.371
3.225	2.928	0.297	3.45	0.691	900	1.413	11.121	2.224	17.460
3.225	2.858	0.367	3.32	0.664	1200	1.884	10.306	2.061	16.182
3.225	2.808	0.417	3.29	0.658	1500	2.355	09.369	1.874	14.709

Table 3.36

Al + 30 wt% c/s **load – 7.5N** **ρ =1.89 × 10^6 g/cm^3**

RPM –100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	$W \times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
4.182	4.107	0.075	4.328	0.577	300	0.1571	25.259	3.368	13.227
4.182	4.084	0.098	4.276	0.570	600	0.3142	16.503	2.201	08.642
4.182	4.073	0.109	4.378	0.583	900	0.4713	12.237	1.631	06.408
4.182	4.046	0.136	4.506	0.601	1200	0.6284	11.451	1.527	05.996
4.182	4.023	0.159	4.354	0.580	1500	0.7855	10.711	1.428	05.608

Table 3.37

Al + 30 wt% c/s **load – 7.5N** ρ **=1.89 × 10^6 g/cm^3**

RPM –200 **Track Radius – 0.05m** v_s **=1.0472 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.541	3.379	0.162	4.248	0.566	300	0.3142	25.259	3.368	13.227
3.541	3.343	0.198	4.312	0.574	600	0.6284	16.502	2.201	08.642
3.541	3.310	0.231	4.287	0.571	900	0.9426	12.236	1.631	06.408
3.541	3.282	0.259	4.35	0.583	1200	1.2568	11.450	1.526	05.996
3.541	3.244	0.297	4.124	0.549	1500	1.571	10.711	1.428	05.608

Table 3.38

Al + 30 wt% c/s **load – 7.5N** ρ **=1.89 × 10^6 g/cm^3**

RPM –300 **Track Radius – 0.05m** v_s **=1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.878	2.632	0.246	5.297	0.706	300	0.471	27.634	3.6846	43.386
2.878	2.569	0.309	5.14	0.685	600	0.942	17.355	2.3141	27.248
2.878	2.524	0.354	4.82	0.643	900	1.413	13.255	1.7674	20.811
2.878	2.483	0.395	5.094	0.679	1200	1.884	11.093	1.4790	17.416
2.878	2.452	0.426	4.867	0.649	1500	2.355	09.571	1.2761	15.026

Table 3.39

Al + 30 wt% c/s **load – 10N** **ρ =1.89 × 10^6 g/cm^3**

RPM –100 **Track Radius – 0.05m** **v_s =0.5236 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
3.612	3.531	0.081	5.8	0.580	300	0.1571	27.280	2.728	14.286
3.612	3.493	0.119	6.4	0.640	600	0.3142	20.039	2.004	10.494
3.612	3.467	0.145	6.2	0.620	900	0.4713	16.278	1.627	08.524
3.612	3.434	0.178	5.9	0.590	1200	0.6284	14.987	1.498	07.848
3.612	3.406	0.206	6.1	0.610	1500	0.7855	13.875	1.387	07.266

Table 3.40

Al + 30 wt% c/s **load – 10N** **ρ =1.89 × 10^6 g/cm^3**

RPM –200 **Track Radius – 0.05m** **v_s =1.0472 m/s**

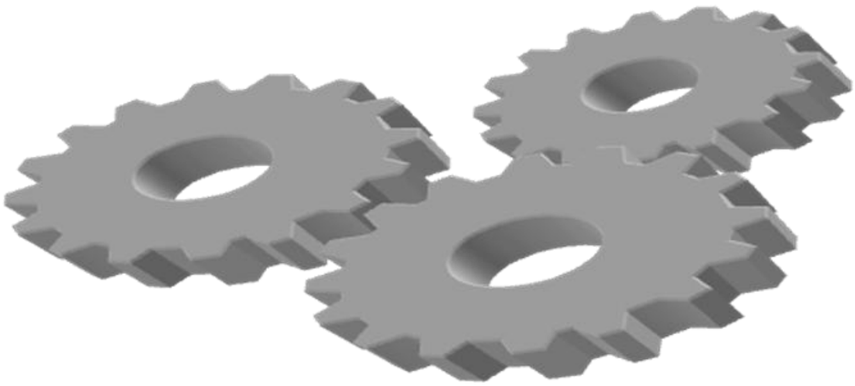
m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
2.765	2.607	0.158	5.4	0.540	300	0.3142	26.606	2.661	27.866
2.765	2.506	0.259	5.32	0.532	600	0.6284	21.807	2.181	22.839
2.765	2.453	0.312	5.21	0.522	900	0.9426	17.513	1.751	18.342
2.765	2.397	0.368	5.45	0.545	1200	1.2568	15.492	1.549	16.225
2.765	2.356	0.409	5.2	0.520	1500	1.571	13.774	1.377	14.426

Table 3.41

Al + 30 wt% c/s **load – 10N** ρ **=1.89 × 10^6 g/cm^3**

RPM –300 **Track Radius – 0.05m** v_s **=1.5708 m/s**

m_1 (gm)	m_2 (gm)	Δm (gm)	F_f (N)	μ	t (sec)	$S_d \times 10^3$ (m)	W $\times 10^{-11}$ (m^3/m)	$W_s \times 10^{-11}$ (m^3/Nm)	$W_v \times 10^{-11}$ (m^3/sec)
4.85	4.603	0.247	6.54	0.654	300	0.471	27.747	2.775	43.562
4.85	4.472	0.378	6.35	0.635	600	0.942	21.231	2.123	33.333
4.85	4.378	0.472	6.421	0.642	900	1.413	17.674	1.767	27.748
4.85	4.301	0.549	6.417	0.641	1200	1.884	15.418	1.542	24.206
4.85	4.243	0.607	6.421	0.642	1500	2.355	13.637	1.364	21.411



RESULTS AND DISCUSSION

4.1 Density Measurement

Density of the samples was calculated theoretically as well as experimentally. From the actual and theoretical densities, void content of the composites were also calculated, as shown in the table. From Fig. 4.1 & 4.2 we can say that density of sintered compacts decreases, with increase in weight percentage of cenospheres in the composites. Also theoretical density is always higher than that of experimental densities due to void contents in the composites.

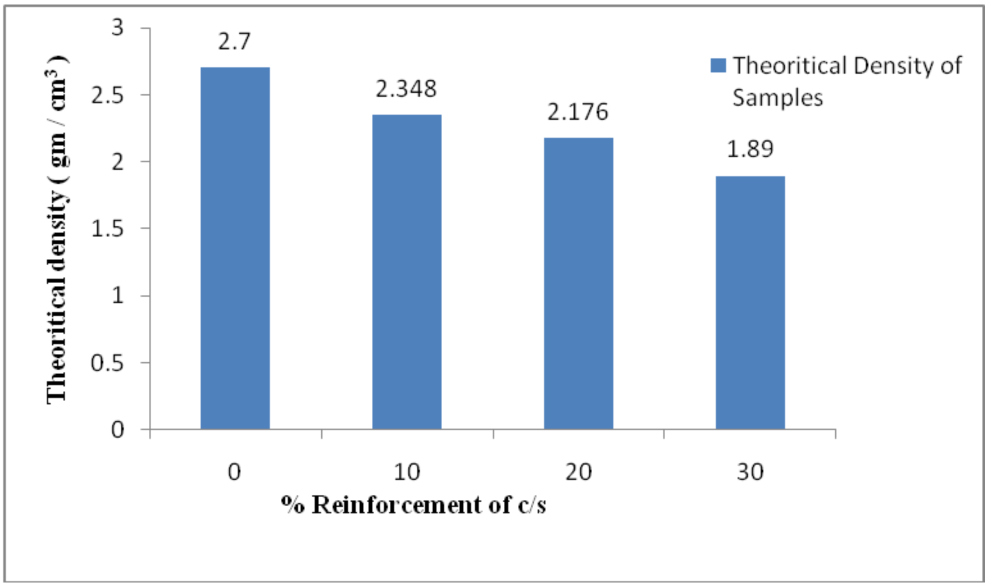


Fig. 4.1 Variation of Theoretical Density Vs % reinforcement of c/s

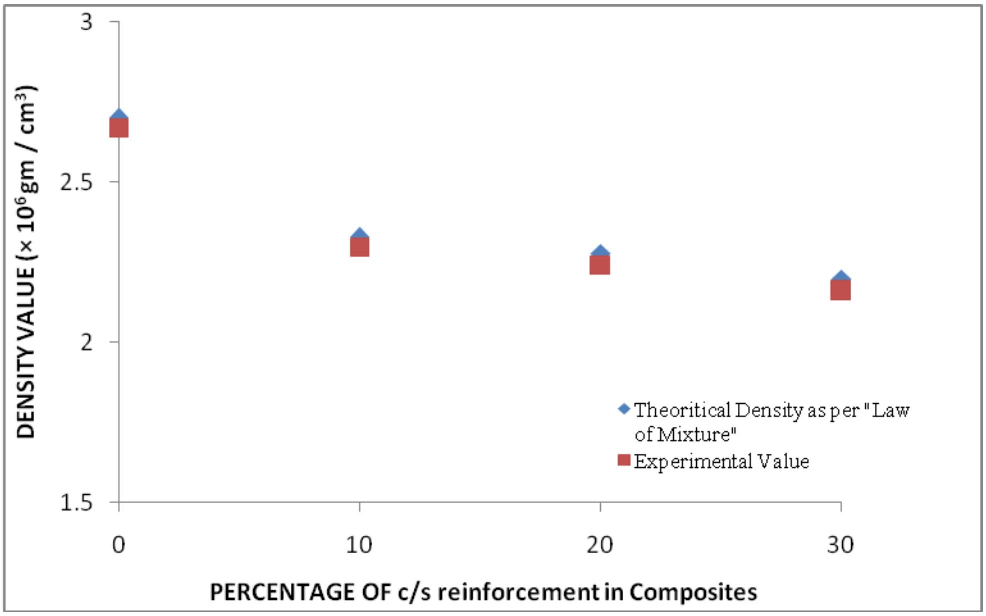


Fig. 4.2 Variation of Theoretical and Actual Density Vs % reinforcement of c/s

4.1.1 Measurement of Void Fraction

Table 4.1 Variations of Void fraction with % Reinforcement of c/s in Composites

% filler	ρ_f	ρ_m	ρ_{Th}	ρ_{Act}	**void**	**void %**
0	0.6	2.7	2.7	2.645	0.02037	2.037037
10	0.6	2.7	2.348	2.315	0.014055	1.405451
20	0.6	2.7	2.176	2.148	0.012868	1.286765
30	0.6	2.7	1.89	1.829	0.032275	3.227513

4.2 Hardness Measurement

The SiC, Al_2O_3 and Aluminide particulate strengthened [58-59] are usually chosen to impart elevated hardness. From the plot, as presented in the **Fig.4.3**, it is observed that, the hardness of fabricated composites is superior to that of pure aluminium. With the increase in cenosphere content, it is found that the hardness of the composite is also increasing.

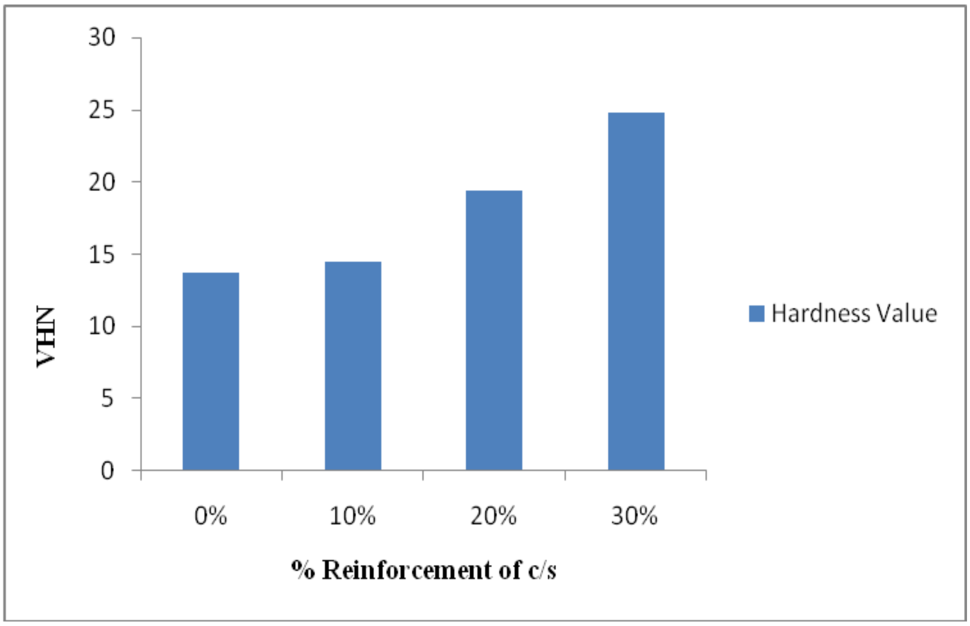


Fig. 4.3 Variation of Vickers Hardness Number with % Reinforcement of c/s in Composites.

4.3 Wear Characteristics

Based on the results, as in tables 3.7.a to 3.18.c, various graphs are plotted and presented in Figs. 4.1 to 4.25 for different percentage of reinforcements of Cenospheres under various test conditions.

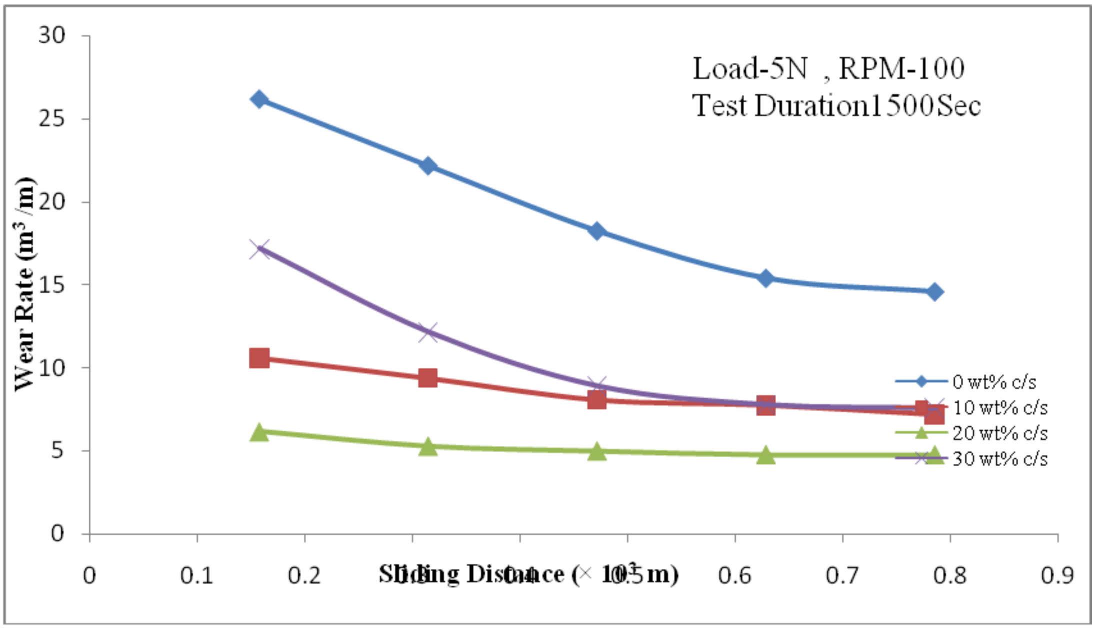


Fig. 4.4 Variation of Abrasive Wear Rate Vs Sliding Distance.

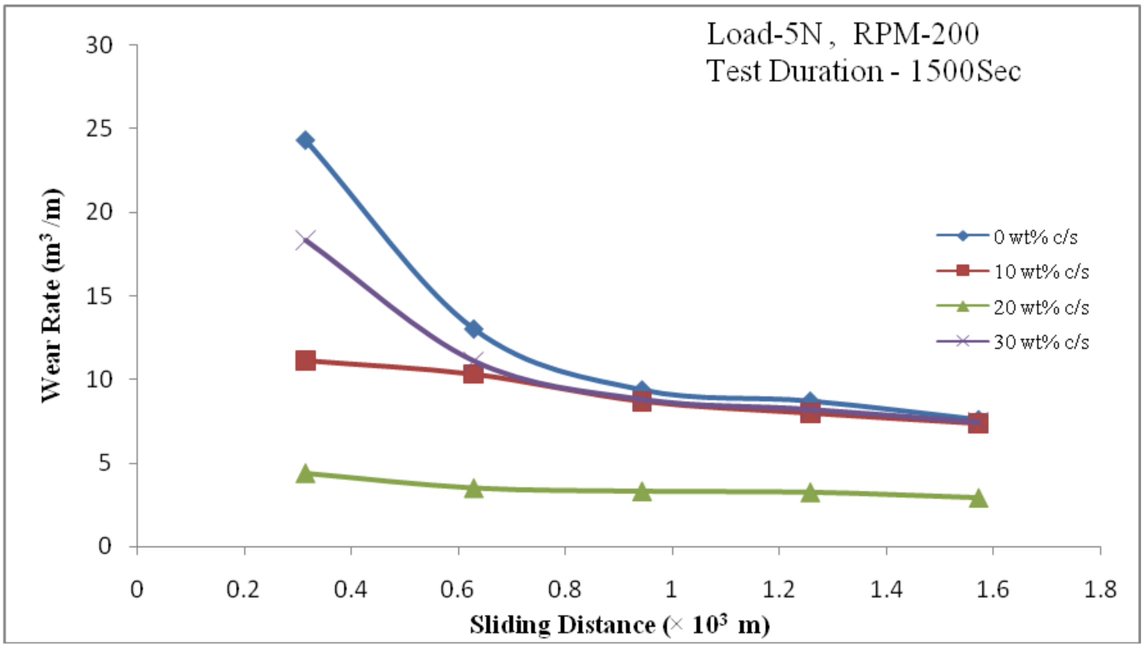


Fig. 4.5 Variation of Abrasive Wear Rate Vs Sliding Distance.

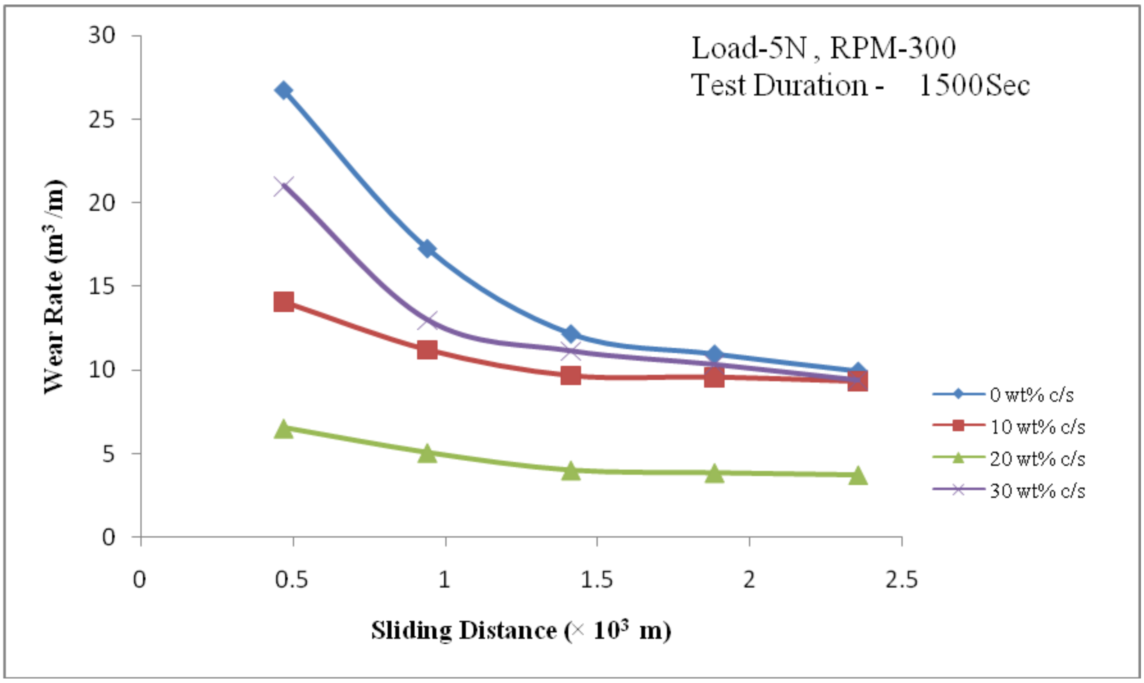


Fig. 4.6 Variation of Abrasive Wear Rate Vs Sliding Distance.

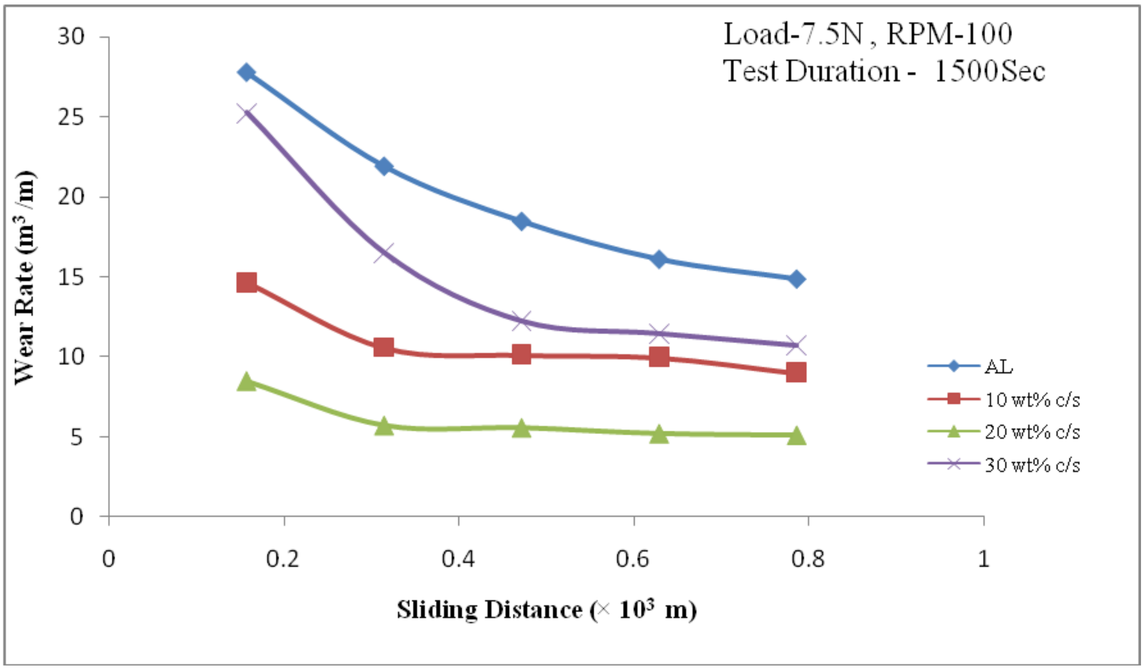


Fig. 4.7 Variation of Abrasive Wear Rate Vs Sliding Distance.

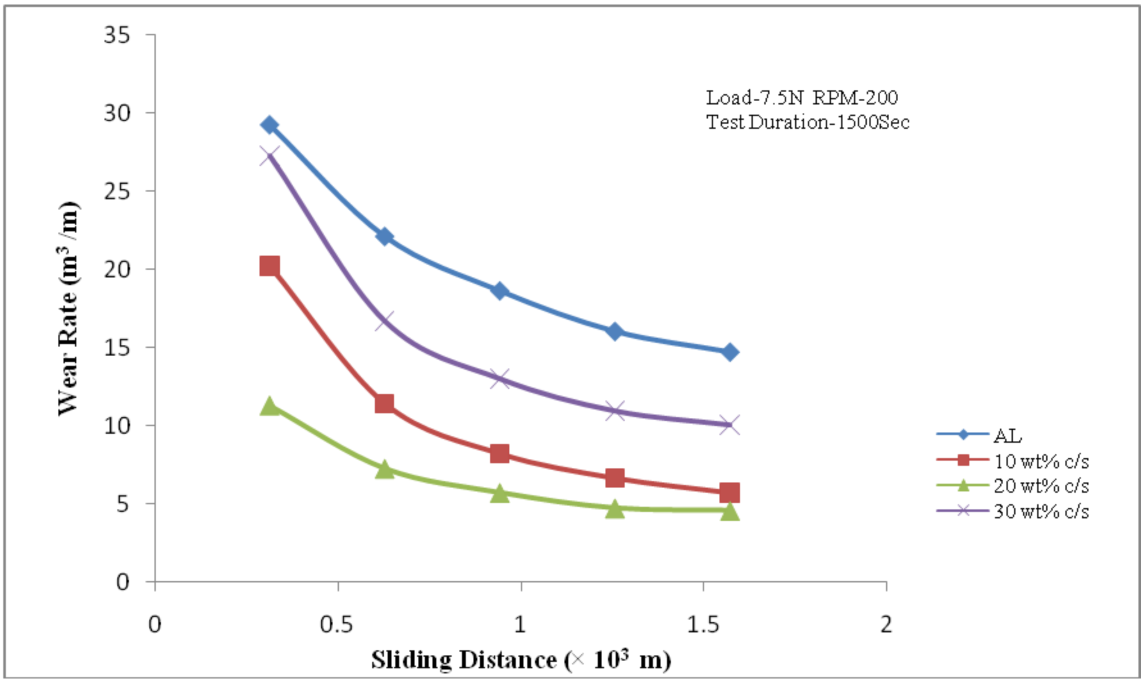


Fig. 4.8 Variation of Abrasive Wear Rate Vs Sliding Distance.

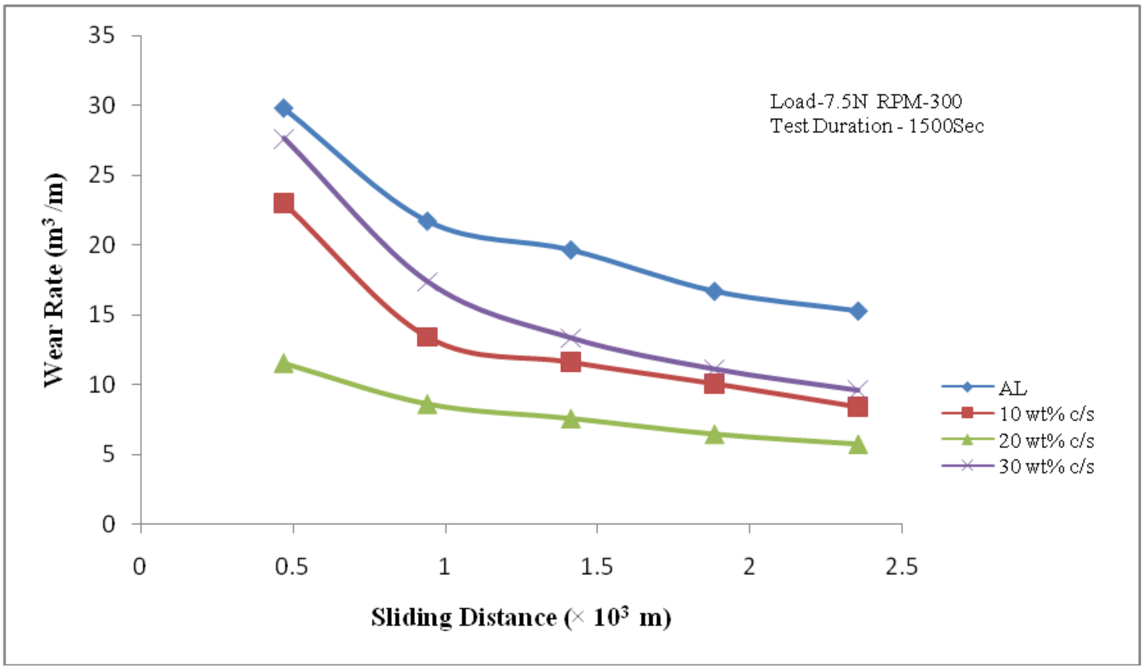


Fig. 4.9 Variation of Abrasive Wear Rate Vs Sliding Distance.

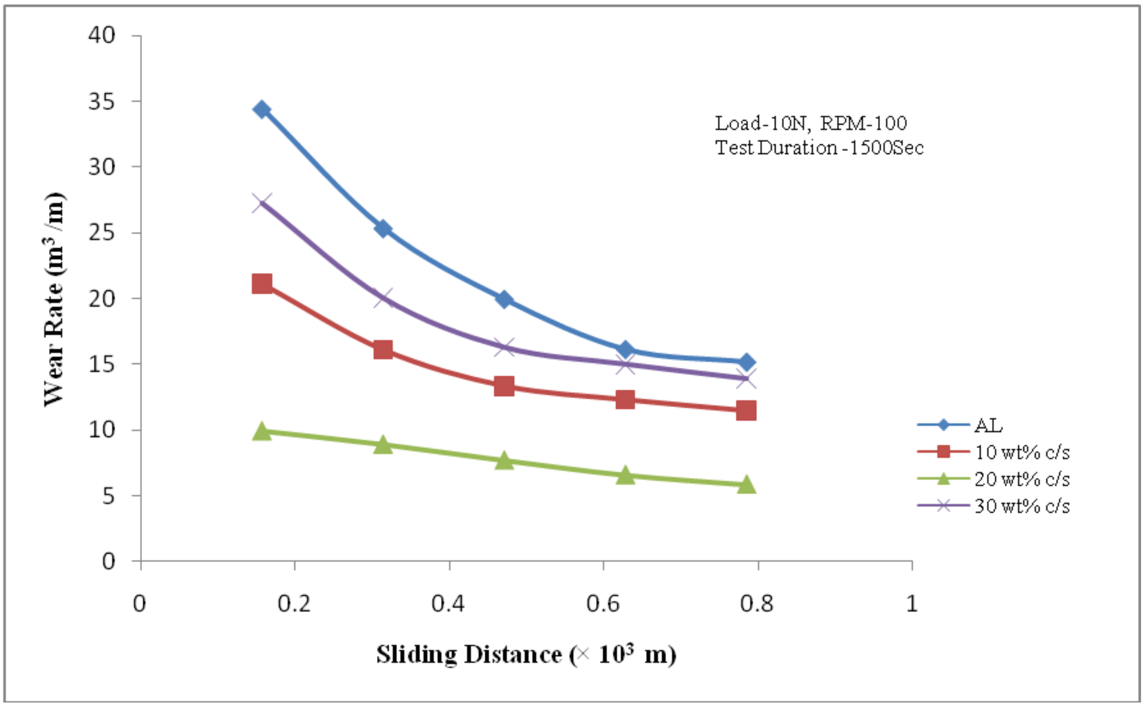


Fig. 4.10 Variation of Abrasive Wear Rate Vs Sliding Distance.

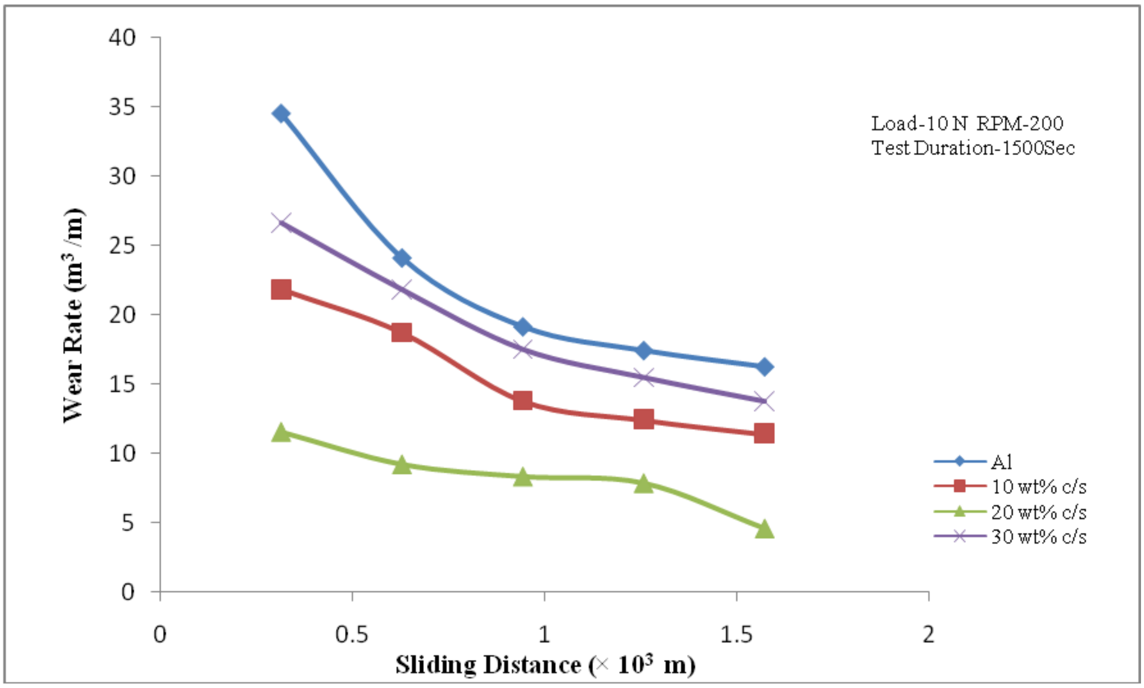


Fig. 4.11 Variation of Abrasive Wear Rate Vs Sliding Distance.

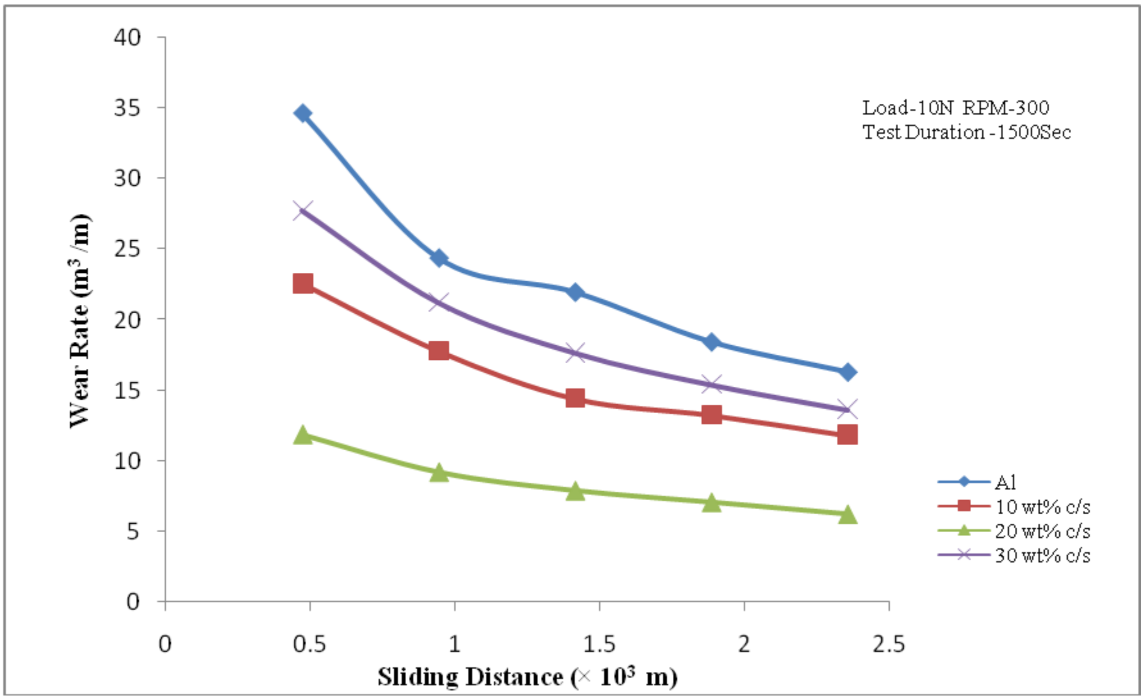


Fig. 4.12 Variation of Abrasive Wear Rate Vs Sliding Distance.

From the plots in the figures 4.4 - 4.12,shows the influence of sliding distance on the abrasive wear of cenosphere dispersed aluminium matrix composite at 100, 200 and 300 RPM i.e. sliding velocity of 0.5236, 1.0472 and 1.5708 m/s for a loads of 5, 7.5 and 10N. It is seen from the plot that with addition of Cenosphere particles the abrasive wear rate of the composite decreases. It is also evident that with addition of Cenosphere Particles the wear resistance of pure Aluminium increases. i.e. the wear rate of pure Aluminium increases with addition of Cenosphere particles in to the Aluminium matrix. Also as the sliding distance increases the wear rate first decreases and then almost remains same for the entire test period. For the present case 20 wt% of the cenosphere filled composite gives optimum results. Further increase of cenosphere particles decreases the wear resistance.

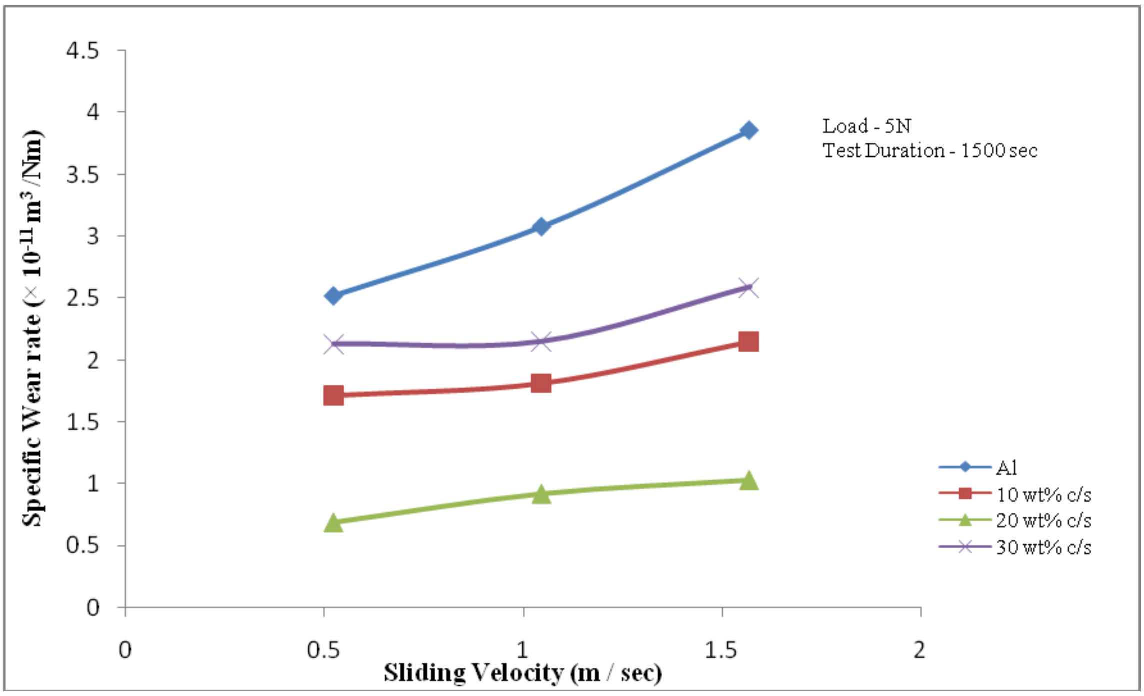


Fig. 4.13 Variation of Specific Wear Rate Vs Sliding Velocity.

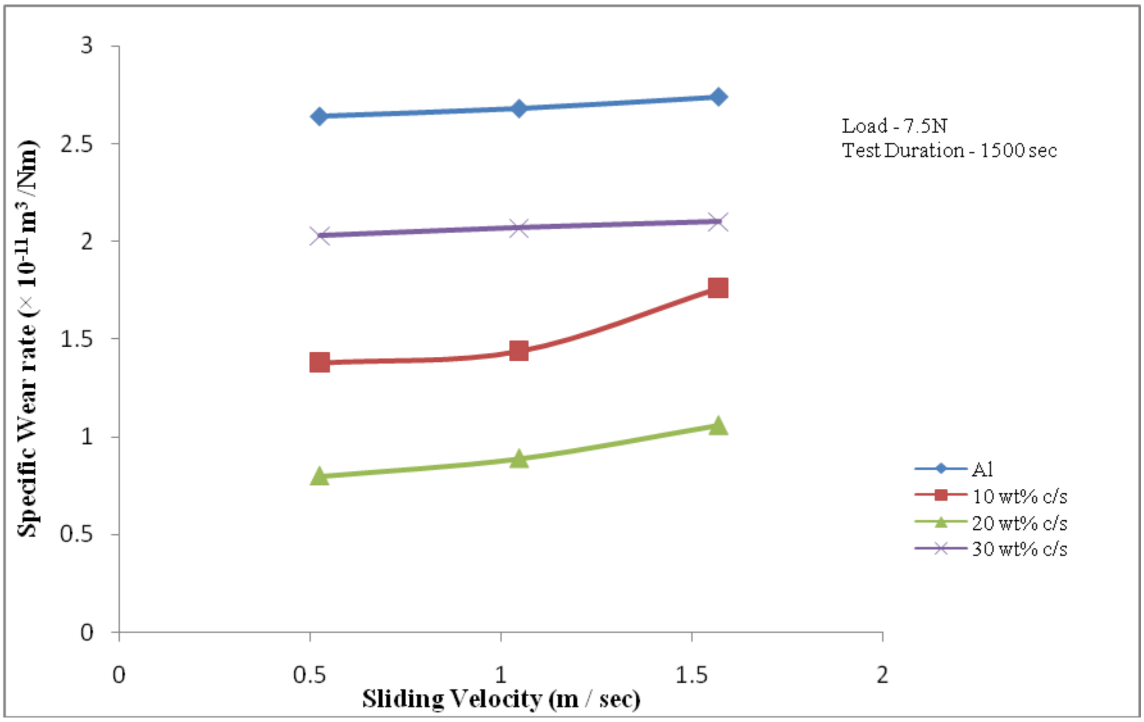


Fig. 4.14 Variation of Specific Wear Rate Vs Sliding Velocity.

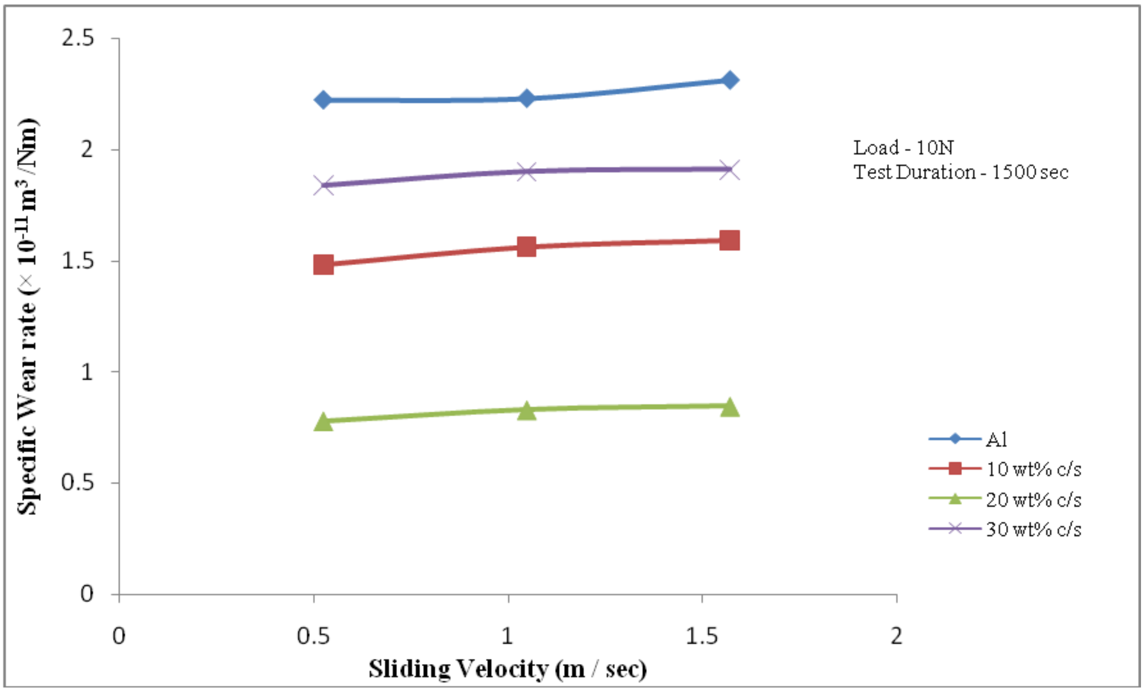


Fig. 4.15 Variation of Specific Wear Rate Vs Sliding Velocity.

From the plots in figures 4.13 – 4.15 shows variation of specific wear rate with sliding velocity. From the plot it is clear that the specific wear rate of the fabricated composite increases with increase in sliding velocity. From the figure it is also clear that the specific wear rate of pure aluminium is always higher than that of the composites. For different weight fraction (10, 20 wt %) of cenosphere filled composite, the specific wear rate decreases. Further increase in the weight fraction of cenosphere (30wt %), the specific wear rate increases to a high value.

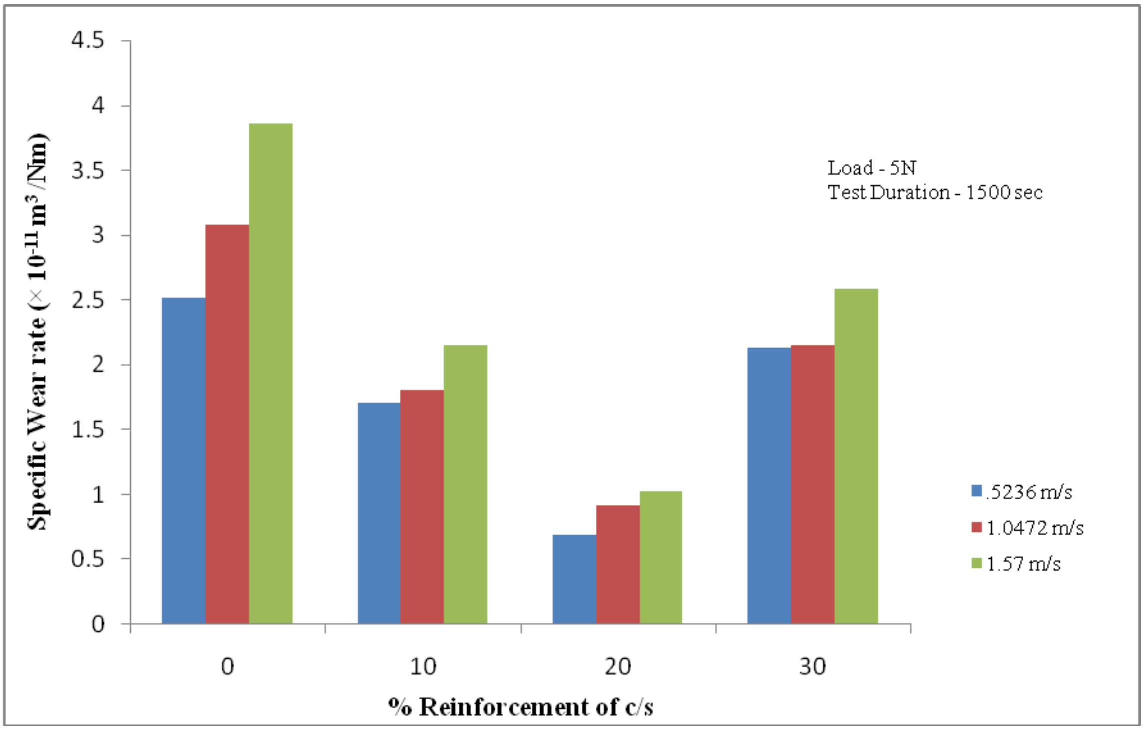


Fig. 4.16 Variation of Specific Wear Rate Vs Weight fraction.

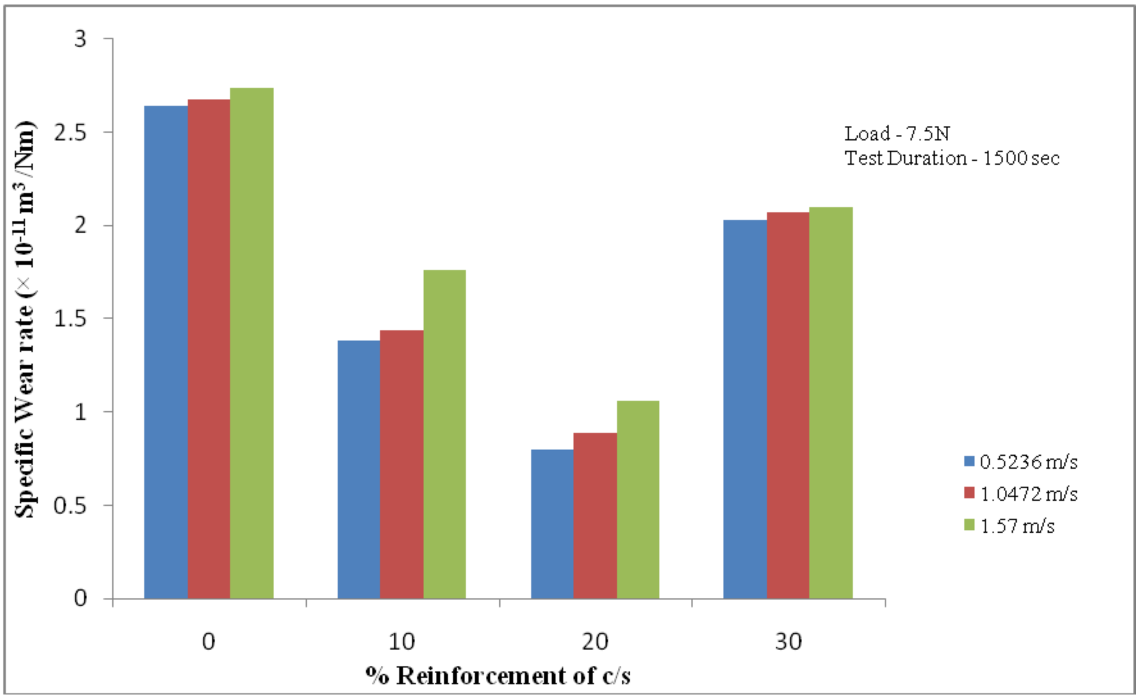


Fig. 4.17 Variation of Specific Wear Rate Vs Weight fraction.

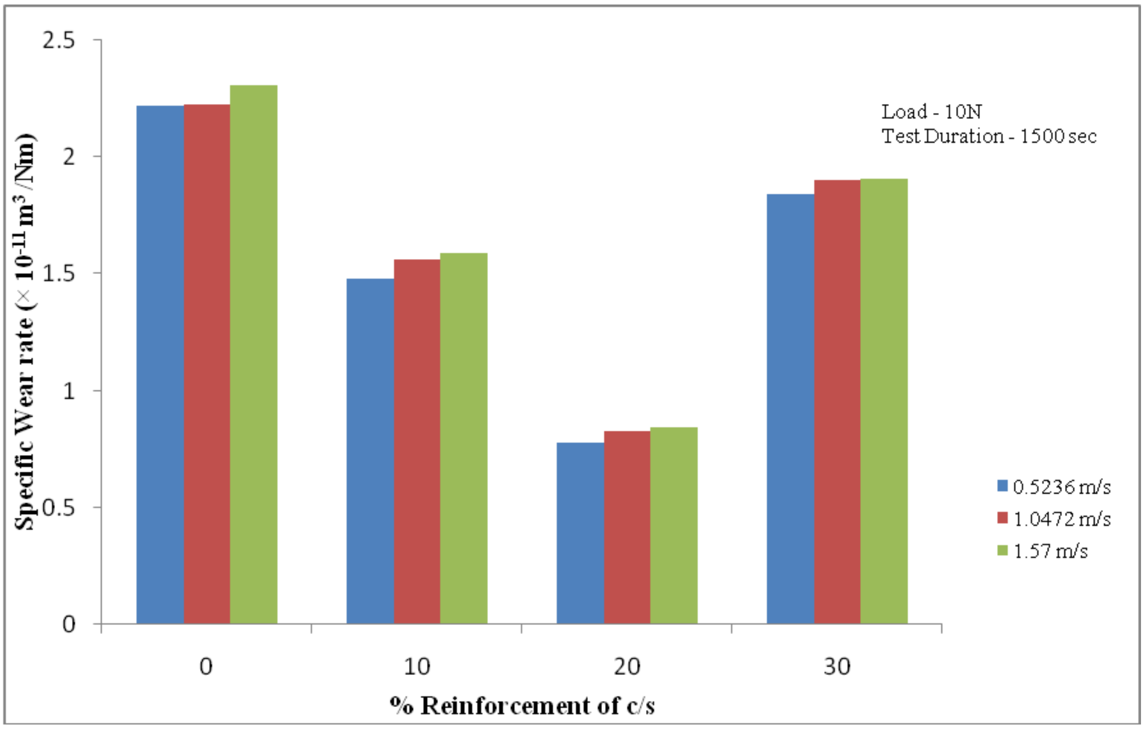


Fig. 4.18 Variation of Specific Wear Rate Vs Weight fraction.

From the plots in the figures 4.16 – 4.18 shows variation of specific wear rate with weight fraction of cenosphere in the composite. It shows that 20 wt% of cenosphere is showing the optimum result in comparison to 10 and 30 wt% of cenosphere in the composite.

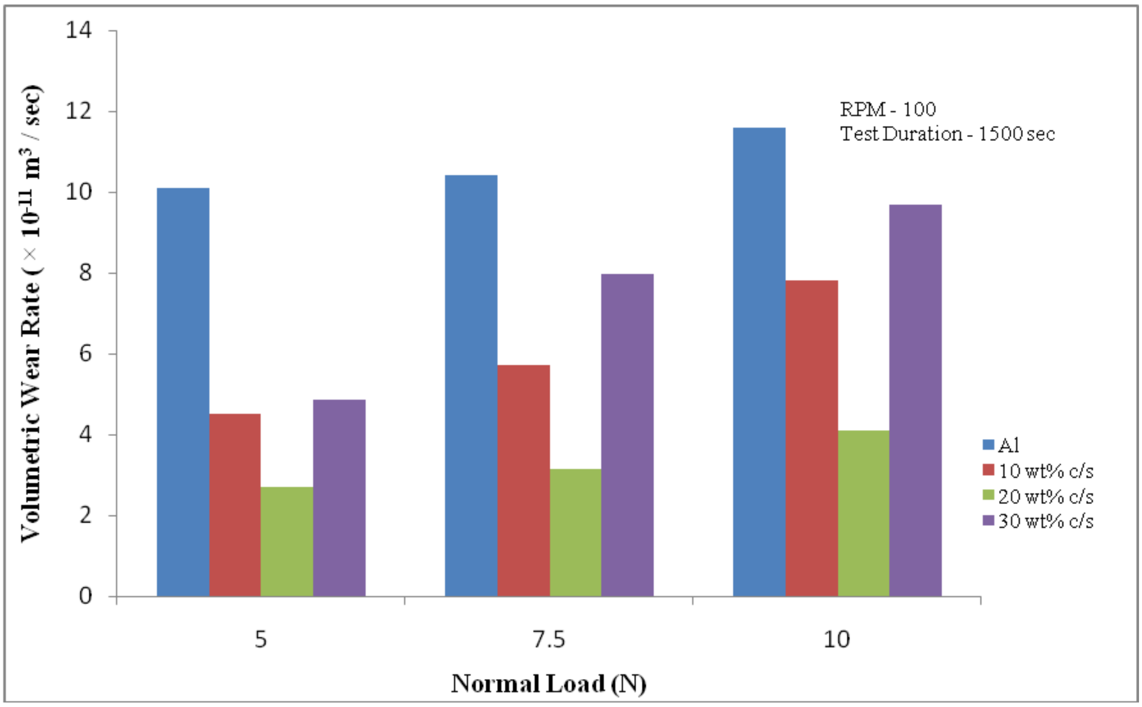


Fig. 4.19 Variation of Volumetric Wear Rate Vs Normal Load.

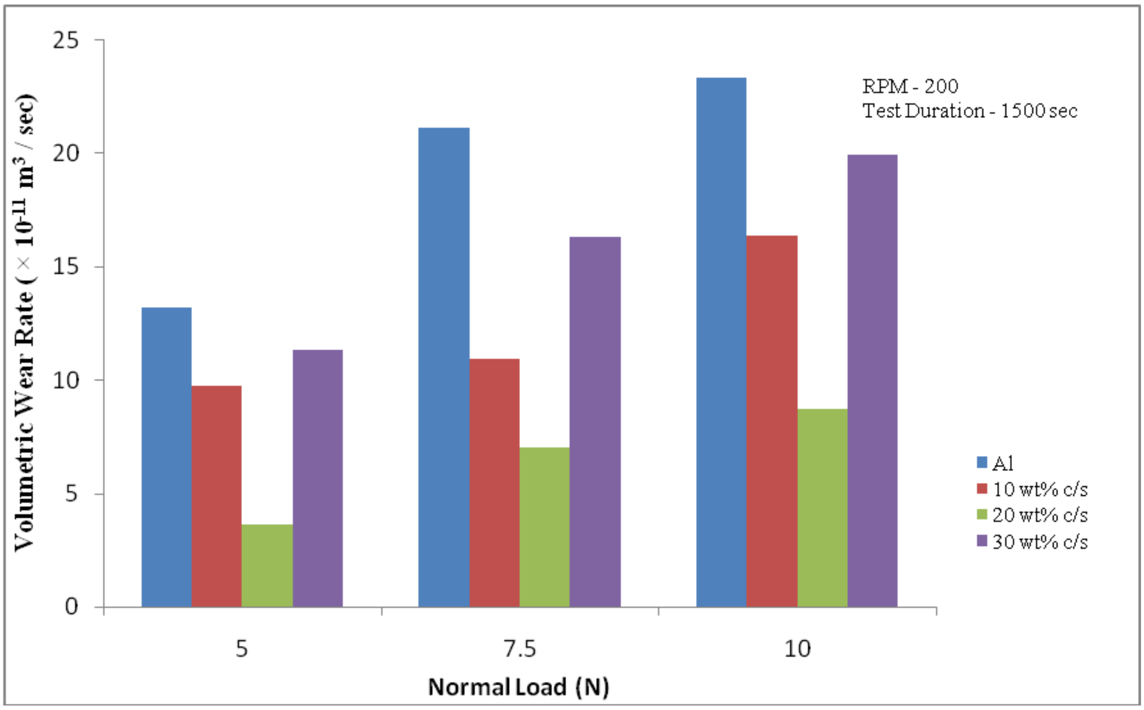


Fig. 4.20 Variation of Volumetric Wear Rate Vs Normal Load.

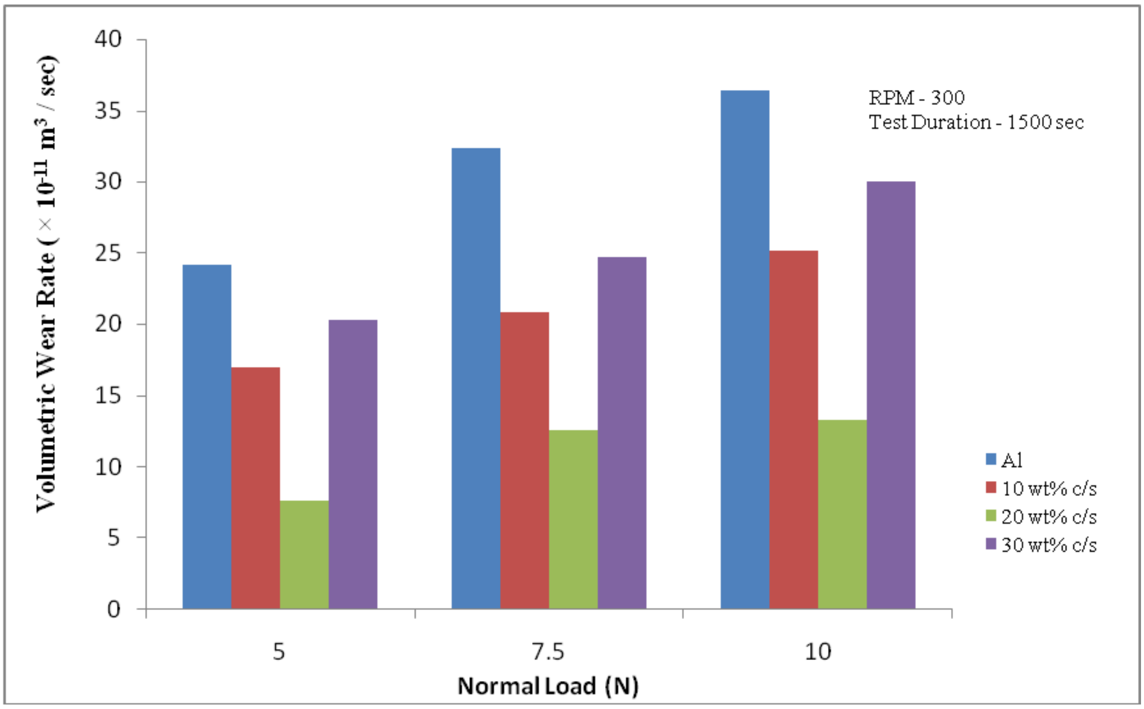


Fig. 4.21 Variation of Volumetric Wear Rate Vs Normal Load.

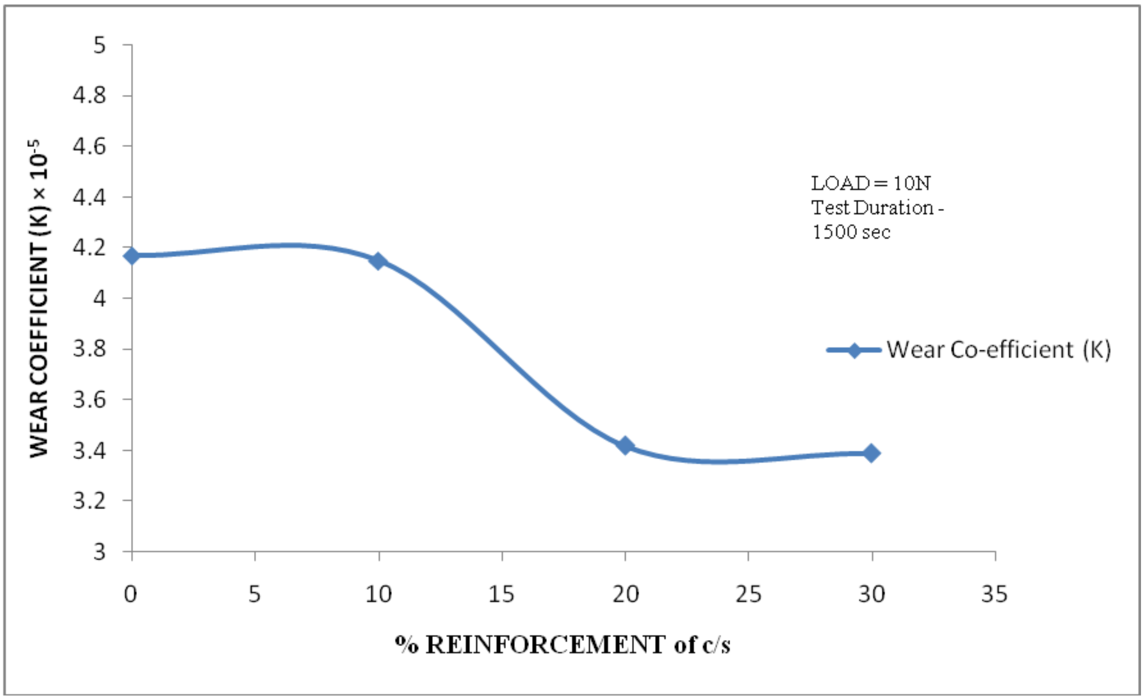


Fig. 4.22 Variation of wear co-efficient with % reinforcement of cenosphere.

Figures 4.19 – 4.21 shows the variation of volumetric wear rate with normal load. It can be observed from the plot, that the volumetric wear rate increases with increase in normal load. This is due to at higher load, the frictional thrust increases, which results in increased de-bonding and fracture. However its variation is less in case of 20% cenosphere filled composite. Plot in the figure 4.22 shows the variation of wear co-efficient with weight fraction of cenospheres. It is clear from the figure that, wear co-efficient is decreasing with the increase in cenosphere addition in the composites. It is apparent that cenosphere addition is beneficial in reducing the wear of the composites.

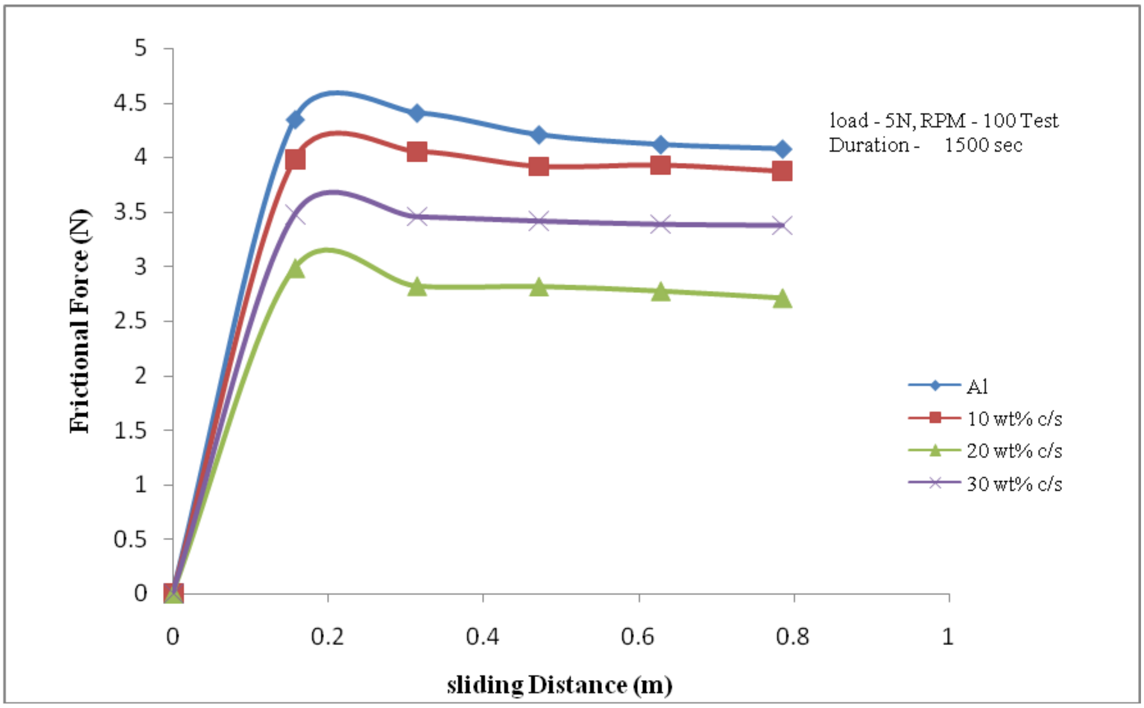


Fig. 4.23 Variation of Frictional force with Sliding Distance.

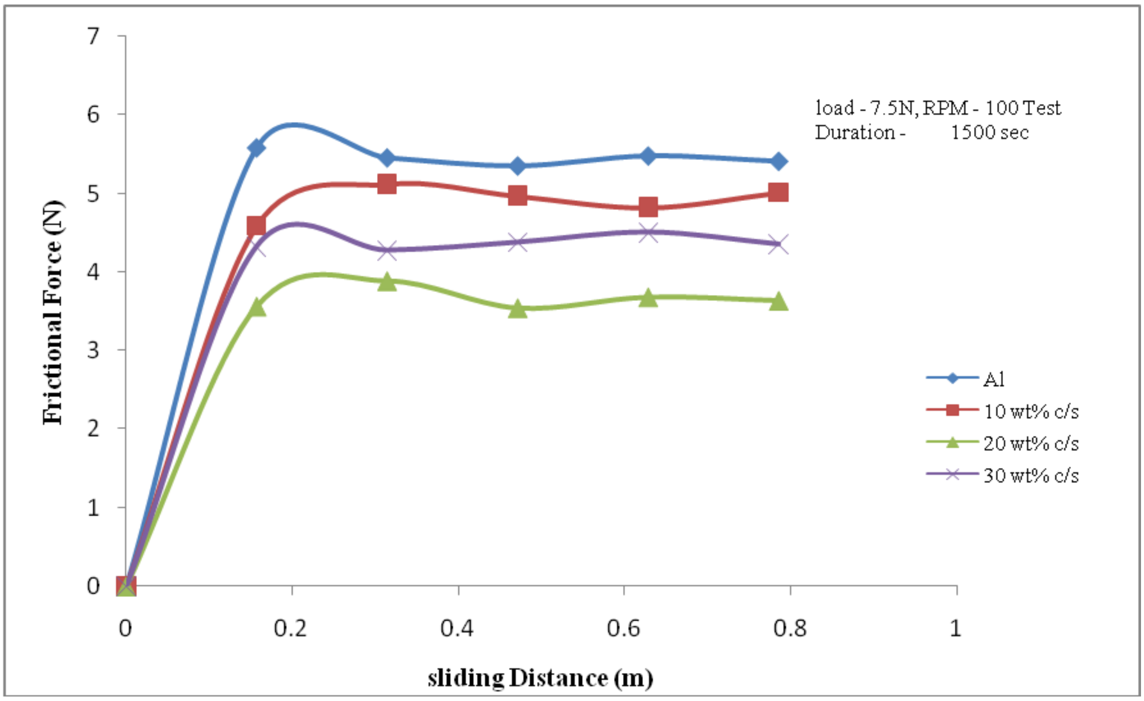


Fig. 4.24 Variation of Frictional force with Sliding Distance.

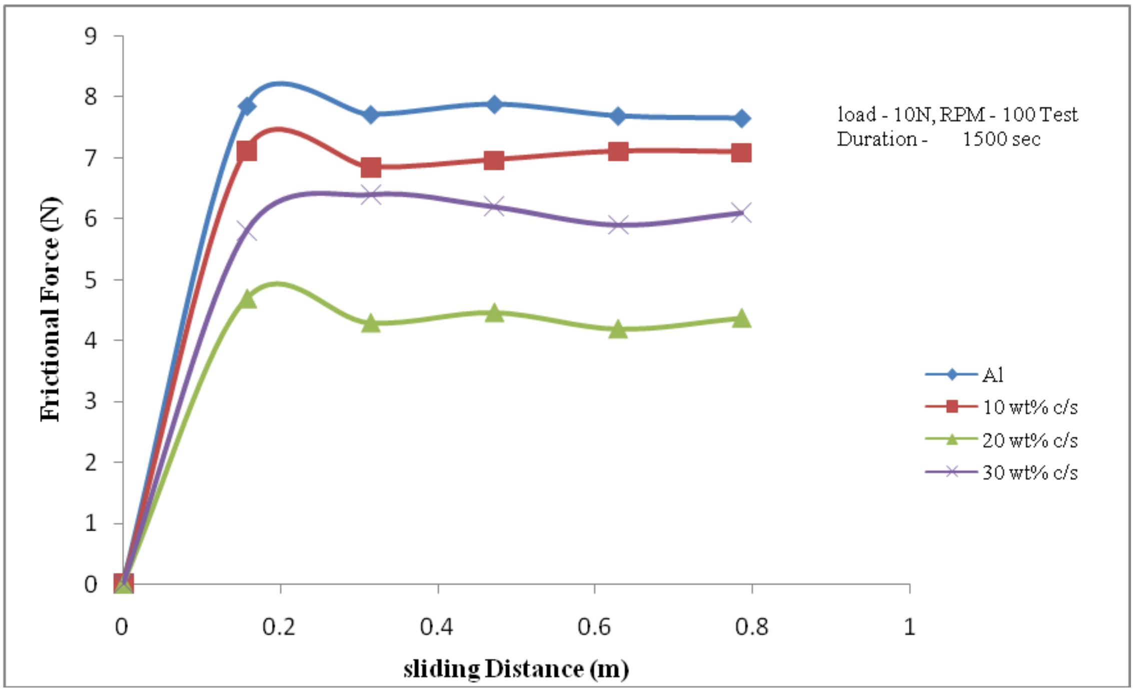


Fig. 4.25 Variation of Frictional force with Sliding Distance.

The variation between frictional force and sliding distance can be studied from the figures 4.23– 4.25. It can be seen from the plot that the frictional force for pure aluminium is greater than the cenosphere dispersed aluminium matrix composites. It is also evident from the graph that the frictional force initially increases to a higher value but as the sliding distance increases, it almost remains constant. It is also clear from the plot that the co-efficient of friction of pure aluminium is higher than that of composites, and 20 weight percentages of cenosphere reinforced aluminium composite shows lowest co-efficient of friction.

4.4 SEM Observation

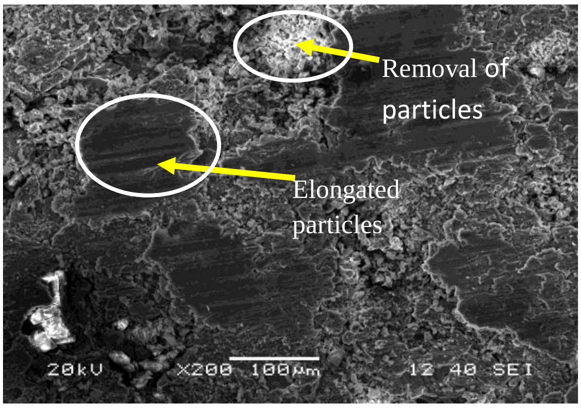


Fig. 4.26(a)

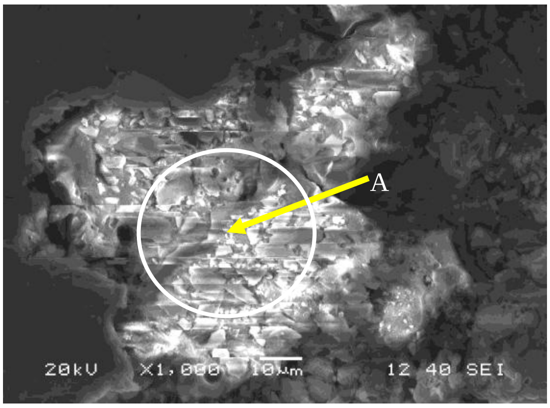


Fig. 4.26(b)

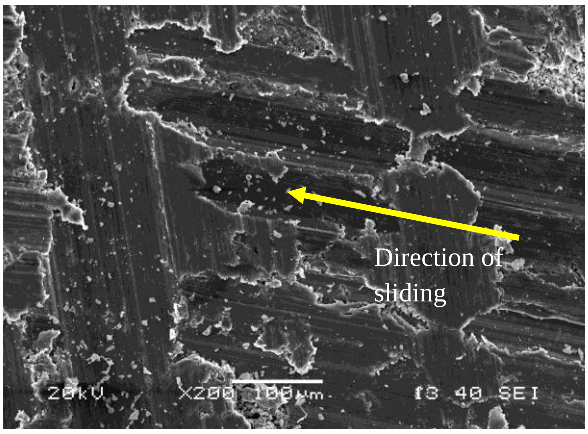


Fig. 4.26(c)

Fig. 4.26 Scanning Electron Micrograph of worn surface of, (a) & (b) 20 wt% of cenosphere in the composite at 200 RPM; an (c) 20 wt% of cenosphere in the composite at 300 RPM

Figure 4.26(a) shows elongated cenosphere particles along the direction of rolling. It also shows shallow abrasive grooves and craters. Because of the shearing action, cenosphere gets elongated along the sliding direction. The crater at higher magnification (× 1000) is shown in fig. 4.26(b). The accumulation of cenosphere particles within the crater is seen in figure, marked (A) Figure 4.26(c) shows the same wt % of cenosphere at higher velocity (300 RPM) with same load. Here also cenosphere particles are elongated but to larger extent and the surface topography at higher magnification also almost similar.

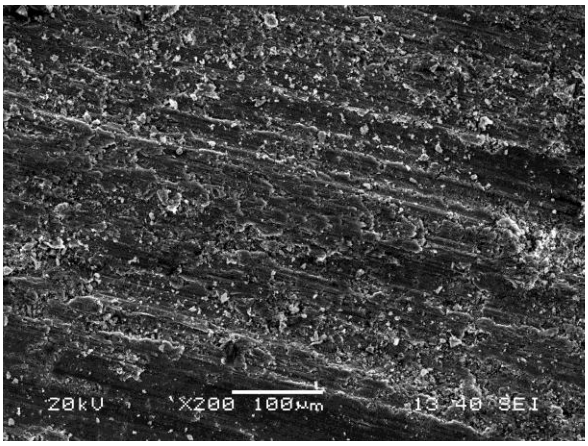


Fig. 4.27(a)

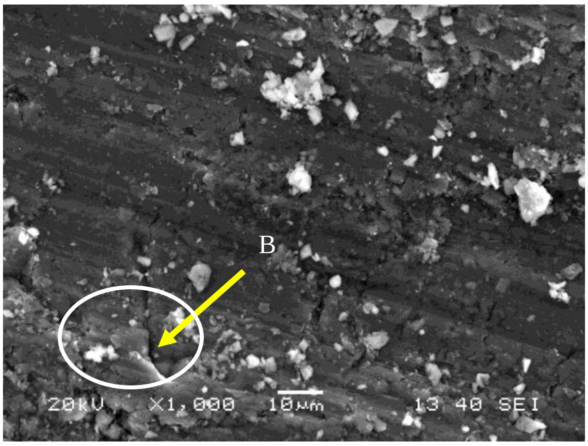
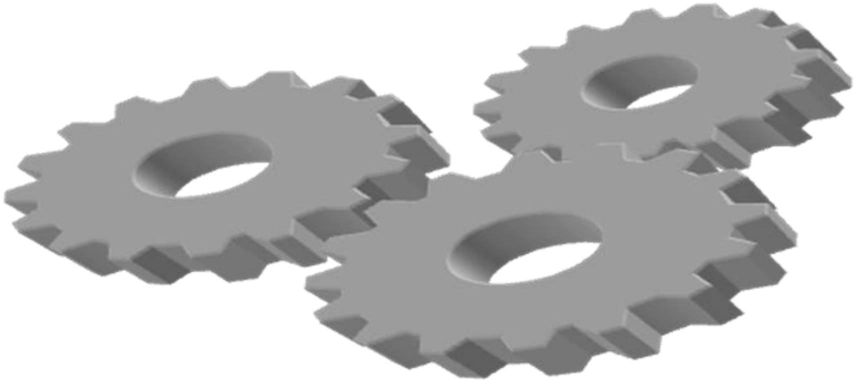


Fig. 4.27(b)

Fig. 4.27 (a) & (b) Scanning Electron Micrograph of worn surface of 30 wt% of cenosphere in the composite at 300 RPM

Figure 4.27 (a) shows the 30 wt% of cenosphere at 300 RPM velocity. When sliding velocity, as well as the wt% of cenosphere increases probably due temperature rise, matrix material gets softened, due to which deboning of cenosphere particles and matrix occurred and the cenosphere particle gets distributed over the matrix. At higher Magnification (× 1000) Wear resistance becomes less; also some cracks are developed on the surface, marked (B) as seen from Figure 4.27 (b)



CONCLUSION

5.1 Conclusion:

This research work on fabrication of Cenosphere dispersed Aluminium matrix composites by powder metallurgy route draws following conclusions:

1. *Cenospheres* are one of the constituent of fly ash, which is one of the abundantly available industrial waste products. It can productively be used to manufacture metal matrix composite by a suitable process, Powder Metallurgy.

2. The density of sintered compacts decreases, with increase in weight percentage of cenospheres in the composites. Also theoretical density is always higher than that of experimental densities due to presence of void in the composites. The void fraction found for the composites are within the limits. Hardness values of the composites increases with increase in cenosphere content. Here we can conclude that the weight fraction of the reinforcements determine the physical properties of the composites.

3. Effect of cenosphere addition enhanced the wear behavior of the composites. A significant improvement in the wear resistance is observed up to 20weight % of cenosphere filled composites.

4. Abrasive wear is very responsive to normal load compared to sliding velocity and increases marginally with increasing sliding velocity.

6. The specific wear rate of the composite increases with an increase in sliding velocity due to the detachment of cenosphere particles with increasing velocity.

7. Co-efficient of friction decreases with increase in the filler content due to the presence on cenosphere particles on the surface.

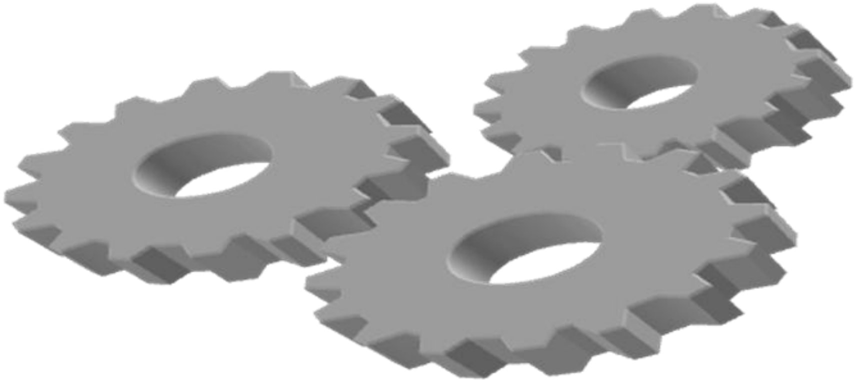
5.2 Recommendations for Further Research

1. In the present investigation powder metallurgy route was used to fabricate the Metal matrix composite. However there exist other manufacturing routes for fabricating the metal matrix

composites. These methods can be tried and analysed, so that a concluding remarks can be made. However the results provided in this thesis can act as a base for reinforcement of cenospheres.

3. In the current work only dry sliding wear test has been carried out on the untreated Cenosphere dispersed Aluminium matrix composites. The same work could be extended to treated composite.

4. Further different other tribological as well as mechanical tests can also be experimented both for treated and untreated composites.



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